

ATLAS search for a heavy gauge boson decaying to a charged lepton and a neutrino in pp collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration*

CERN, Geneva, Switzerland

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Abstract The ATLAS detector at the LHC is used to search for high-mass states, such as heavy charged gauge bosons (W'), decaying to a charged lepton (electron or muon) and a neutrino. Results are presented based on the analysis of pp collisions at a center-of-mass energy of 7 TeV corresponding to an integrated luminosity of 4.7 fb^{-1} . No excess beyond Standard Model expectations is observed. A W' with Sequential Standard Model couplings is excluded at the 95 % credibility level for masses up to 2.55 TeV. Excited chiral bosons (W^*) with equivalent coupling strength are excluded for masses up to 2.42 TeV.

1 Introduction

High-energy collisions at the CERN Large Hadron Collider provide the opportunity to search unexplored regions for physics beyond the Standard Model (SM) of strong and electroweak interactions. One extension common to many models is the existence of additional heavy gauge bosons, the charged ones commonly denoted W' . Such particles are most easily searched for in their decay to a charged lepton (electron or muon) and a neutrino.

This letter describes such a search performed using 7 TeV pp collision data collected with the ATLAS detector during 2011 corresponding to a total integrated luminosity of 4.7 fb^{-1} . The data are used to extend current limits [1–4] on σB (cross section times branching fraction) for $W' \rightarrow \ell \nu$ ($\ell = e$ or μ) as a function of W' mass. Limits are evaluated in the context of the Sequential Standard Model (SSM), i.e. the extended gauge model of Ref. [5] with the W' coupling to WZ set to zero. In this model, the W' has the same couplings to fermions as the SM W boson and a width which increases linearly with the W' mass. A previous letter [4] described a similar search with a subset (1.0 fb^{-1}) of the

data used in this study. Here the mass range of the search is extended and the limits in the previously covered region are significantly improved because of the fivefold increase in integrated luminosity. An improved lower mass limit assuming SSM coupling strength is also reported.

A search is also performed for the charged partners, denoted W^* , of the chiral boson excitations described in Ref. [6] with theoretical motivation in Ref. [7]. The anomalous (magnetic-moment type) coupling of the W^* leads to kinematic distributions significantly different from those of the W' . The previous search for this resonance [3] was performed using data acquired in 2010 with an integrated luminosity less than 1 % of that used here. The search region is expanded to both lower and higher masses and the limits are considerably improved in the region covered by the previous search. A lower mass limit is evaluated by fixing the W^* coupling strengths to give the same partial decay widths as the SSM W' .

The analysis presented here identifies event candidates in the electron and muon channels, sets separate limits for $W'/W^* \rightarrow e\nu$ and $W'/W^* \rightarrow \mu\nu$, and then combines these assuming a common branching fraction for the two channels. The kinematic variable used to identify the W'/W^* is the transverse mass

$$m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \phi_{\ell\nu})}, \quad (1)$$

whose distribution has a Jacobian peak and falls sharply above the resonance mass. Here p_T is the lepton transverse momentum, E_T^{miss} is the magnitude of the missing transverse momentum (missing E_T), and $\phi_{\ell\nu}$ is the angle between the p_T and missing E_T vectors. Throughout this letter, transverse refers to the plane perpendicular to the colliding beams, longitudinal means parallel to the beams, θ and φ are the polar and azimuthal angles with respect to the longitudinal direction, and pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$.

Figure 1 shows the electron η and the m_T spectra for $W' \rightarrow e\nu$ and $W^* \rightarrow e\nu$, with $m_{W'} = m_{W^*} = 2.0$ TeV, from

* e-mail: atlas.publications@cern.ch

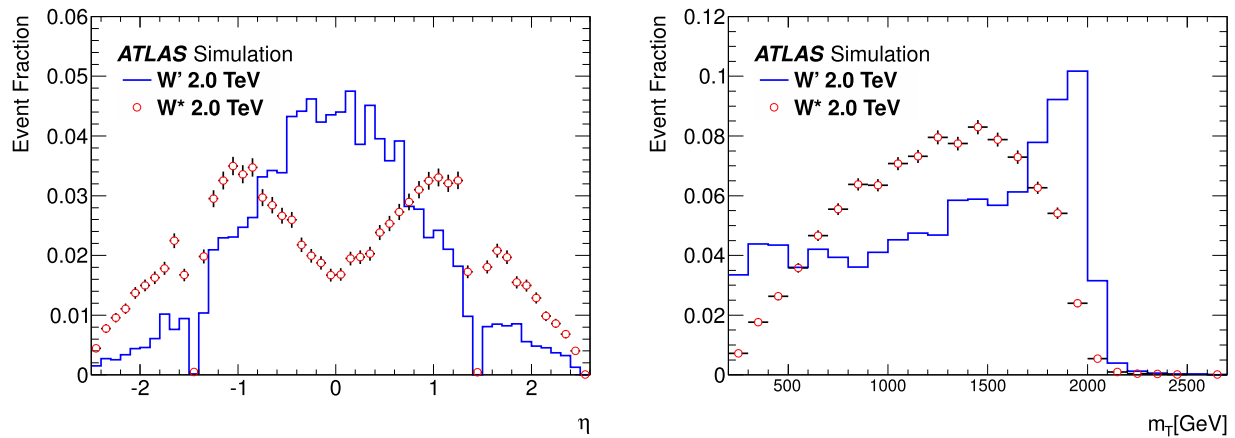


Fig. 1 Reconstructed electron η (left) and m_T (right) distributions for $W' \rightarrow e\nu$ and $W^* \rightarrow e\nu$ with $m_{W'} = m_{W^*} = 2.0$ TeV. All distributions are normalised to unit area

the event generation, detector simulation and reconstruction described below. The difference in kinematic shape is evident: the W' is more central in pseudorapidity and has a sharper m_T spectrum.

The main background to the $W'/W^* \rightarrow \ell\nu$ signal comes from the high- m_T tail of SM W boson decay to the same final state. Other backgrounds are Z bosons decaying into two leptons where one lepton is not reconstructed, W or Z decaying to τ leptons where a τ subsequently decays to an electron or muon, and diboson production. These are collectively referred to as the electroweak (EW) background. In addition, there is a background contribution from $t\bar{t}$ and single-top production which is most important for the lowest W' masses considered here, where it constitutes about 15 % of the background after event selection. Other strong-interaction background sources, where a light or heavy hadron decays semileptonically or a jet is misidentified as an electron, are estimated to be at most 10 % of the total background in the electron channel and a negligible fraction in the muon channel. These are called QCD background in the following.

2 Detector, trigger and reconstruction

The ATLAS detector [8] has three major components: the inner tracking detector, the calorimeter and the muon spectrometer. Charged particle tracks and vertices are reconstructed with silicon pixel and silicon strip detectors covering $|\eta| < 2.5$ and straw-tube transition radiation detectors covering $|\eta| < 2.0$, all immersed in a homogeneous 2 T magnetic field provided by a superconducting solenoid. This tracking detector is surrounded by a finely segmented, hermetic calorimeter system that covers $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers. It uses

liquid argon for the inner EM (electromagnetic) compartment followed by a hadronic compartment based on scintillating tiles in the central region ($|\eta| < 1.7$) and liquid argon for higher $|\eta|$. Outside the calorimeter, there is a muon spectrometer with air-core toroids providing a magnetic field, whose integral averages about 3 Tm. The deflection of the muons in the magnetic field is measured with three layers of precision drift-tube chambers for $|\eta| < 2.0$ and one layer of cathode-strip chambers followed by two layers of drift-tube chambers for $2.0 < |\eta| < 2.7$. Additional resistive-plate and thin-gap chambers provide muon triggering capability and measurement of the φ coordinate.

The data used in the electron channel are recorded with a trigger requiring the presence of an EM cluster (i.e. an energy cluster in the EM compartment of the calorimeter) with energy corresponding to an electron with $p_T > 80$ GeV. This substantial increase over the p_T threshold used in the previous analysis [4] is required to maintain high efficiency (above 99 %) and keep the trigger rate at a tolerable level for the high luminosity used to acquire the bulk of the data. For the muon channel, matching tracks in the muon spectrometer and inner detector with combined $p_T > 22$ GeV are used to select events. Events are also recorded if a muon with $p_T > 40$ GeV is found in the muon spectrometer. These are the same p_T thresholds used in the previous analysis and, despite stricter hit requirements imposed for the higher-luminosity data, the muon trigger efficiency remains 80–90 % in the regions of interest.

Each EM cluster with $E_T > 85$ GeV and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ is considered as an electron candidate if it matches an inner detector track. The electron direction is defined as that of the reconstructed track and its energy as that of the cluster, with a small η -dependent energy scale correction. The energy resolution is 2 % for $E_T \approx 50$ GeV and approaches 1 % in the high- E_T range relevant to this analysis. To discriminate against hadronic jets, requirements are

imposed on the lateral shower shapes in the first two layers of the EM compartment of the calorimeter and on the fraction of energy leaking into the hadronic compartment. A hit in the first pixel layer is required to reduce background from photon conversions in the inner detector material. These requirements result in about 90 % identification efficiency for electrons with $E_T > 85$ GeV and a 2×10^{-4} probability to falsely identify jets as electrons before isolation requirements are imposed [9].

Muons are required to have $p_T > 25$ GeV, where the momentum of the muon is obtained by combining the inner detector and muon spectrometer measurements. The p_T threshold allows the high trigger efficiency. To ensure precise measurement of the momentum, muons are required to have hits in all three muon layers and are restricted to those η -ranges where the muon spectrometer alignment is best understood: approximately $|\eta| < 1.0$ and $1.3 < |\eta| < 2.0$. The average momentum resolution is about 15 % at $p_T = 1$ TeV. About 80 % of the muons in these η -ranges are reconstructed, with most of the loss coming from regions with limited detector coverage.

The missing E_T in each event is evaluated by summing over energy-calibrated physics objects (jets, photons and leptons) and adding corrections for calorimeter deposits away from these objects [10]. This is an improvement over the previous analysis which did not include the energy calibration.

This analysis makes use of all the $\sqrt{s} = 7$ TeV data collected in 2011 for which the relevant detector systems were operating properly. The integrated luminosity for the data used in this study is 4.7 fb^{-1} in both the electron and muon decay channels. The uncertainty on this measurement is 3.9 % [11, 12].

3 Simulation

Except for the QCD background, which is measured with data, expected signal and background levels are evaluated using simulated samples, normalised with calculated cross sections and the integrated luminosity of the data.

The W' signal and the W/Z boson backgrounds are generated with PYTHIA 6.421 [13] using the modified leading-order (LO) parton distribution functions (PDFs) of Ref. [14]. PYTHIA is also used for the $W^* \rightarrow \ell\nu$ event generation, but with initial kinematics generated at LO with COMPHEP [15] using the CTEQ6L1 PDFs [16]. The $t\bar{t}$ background is generated with MC@NLO 3.41 [17] using the CTEQ6.6 [18] PDFs. For all samples, final-state photon radiation is handled by PHOTOS [19]. The ATLAS full detector simulation [20] based on GEANT4 [21] is used to propagate the particles and account for the response of the detector.

The PYTHIA signal model for W' has $V-A$ SM couplings to fermions but does not include interference between W and W' . For both W' and W^* , decays to channels other than $e\nu$ and $\mu\nu$, including $\tau\nu$, ud , sc and tb , are included in the calculation of the widths but are not explicitly included as signal or background. At high mass ($m_{W'} > 1$ TeV), the branching fraction to each of the lepton decay channels is 8.2 %.

The $W \rightarrow \ell\nu$ events are reweighted to have the NNLO (next-to-next-to-leading-order) QCD mass dependence of ZWPROD [22] following the G_μ scheme [23] and using the MSTW2008 PDFs [24]. Higher-order electroweak corrections (in addition to the photon radiation included in the simulation) are calculated using HORACE [23, 25]. In the high-mass region of interest, the electroweak corrections reduce the cross sections by 11 % at $m_{\ell\nu} = 1$ TeV and by 18 % at $m_{\ell\nu} = 2$ TeV.

The $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ cross sections are calculated at NNLO using FEWZ [26, 27] with the same PDFs, scheme and electroweak corrections used in the ZWPROD event reweighting. The $W' \rightarrow \ell\nu$ cross sections are calculated in the same way, except the electroweak corrections beyond final-state radiation are not included because the calculation for the SM W cannot be applied directly. The $t\bar{t}$ cross section is calculated at approximate-NNLO [28–30] assuming a top-quark mass of 172.5 GeV. The $W^* \rightarrow \ell\nu$ cross-section evaluation is performed with COMPHEP using the CTEQ6L1 PDFs (i.e. same as the event generation). The signal and most important background cross sections are listed in Table 1.

Cross-section uncertainties for $W' \rightarrow \ell\nu$ and the W/Z [9] and $t\bar{t}$ [31] backgrounds are estimated from the MSTW2008 PDF error sets, the difference between the MSTW2008 and CTEQ6.6 PDFs, and variation of renormalization and factorization scales by a factor of two. The estimates from the three sources are combined in quadrature. Most of the net uncertainty comes from the PDF error sets and the MSTW-CTEQ difference, in roughly equal proportion. The $W^* \rightarrow \ell\nu$ cross-section uncertainties are evaluated with the CTEQ61 [16] PDF error sets.

4 Event selection

The primary vertex for each event is required to have at least three tracks with $p_T > 0.4$ GeV and to have a longitudinal distance less than 200 mm from the center of the collision region. Due to the high luminosity, there are an average of more than ten additional interactions per event in the data used for this analysis. The primary vertex is defined to be the one with the highest summed track p_T^2 . Spurious tails in missing E_T , arising from calorimeter noise and other detector problems are suppressed by checking the quality of

Table 1 Calculated values of σB for $W' \rightarrow \ell\nu$, $W^* \rightarrow \ell\nu$ and the leading backgrounds. The value for $t\bar{t} \rightarrow \ell X$ includes all final states with at least one lepton (e , μ or τ). The others are exclusive and are used for both $\ell = e$ and $\ell = \mu$. All calculations are NNLO except W^* which is LO and $t\bar{t}$ which is approximate-NNLO

| Process | Mass [GeV] | σB [pb] |
|-------------------------------------|------------|-----------------|
| $W' \rightarrow \ell\nu$ | 300 | 130.5 |
| | 400 | 41.6 |
| | 500 | 17.25 |
| | 600 | 8.27 |
| | 750 | 3.20 |
| | 1000 | 0.837 |
| | 1250 | 0.261 |
| | 1500 | 0.0887 |
| | 1750 | 0.0325 |
| | 2000 | 0.0126 |
| | 2250 | 0.00526 |
| | 2500 | 0.00235 |
| | 2750 | 0.001156 |
| | 3000 | 0.000643 |
| $W^* \rightarrow \ell\nu$ | 400 | 29.6 |
| | 500 | 12.6 |
| | 750 | 2.34 |
| | 1000 | 0.610 |
| | 1250 | 0.188 |
| | 1500 | 0.0636 |
| | 1750 | 0.0226 |
| | 2000 | 0.00819 |
| | 2250 | 0.00299 |
| | 2500 | 0.000109 |
| $W \rightarrow \ell\nu$ | 2750 | 0.000391 |
| | 3000 | 0.000138 |
| | | |
| | | |
| $Z/\gamma^* \rightarrow \ell\ell$ | | 10460 |
| $(m_{Z/\gamma^*} > 60 \text{ GeV})$ | | 989 |
| $t\bar{t} \rightarrow \ell X$ | | 89.4 |

each reconstructed jet and discarding events where any jet has a shape indicating such problems, following Ref. [32]. In addition, the inner detector track associated with the electron or muon is required to be compatible with originating from the primary vertex, specifically to have transverse distance of closest approach $|d_0| < 1$ mm and longitudinal distance at this point $|z_0| < 5$ mm in the electron channel. For the muon channel, the requirements are $|d_0| < 0.2$ mm and $|z_0| < 1$ mm. Events are required to have exactly one candidate electron or one candidate muon satisfying these requirements.

To suppress the QCD background, the lepton is required to be isolated. In the electron channel, the isolation energy is measured with the calorimeter in a cone $\Delta R < 0.4$

Table 2 Expected numbers of events from the various background sources in each decay channel for $m_T > 794$ GeV, the region used to search for a W' with a mass of 1000 GeV in the electron and muon channels. The $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ entries include the expected contributions from the τ -lepton. The uncertainties are those from the Monte Carlo statistics

| | $e\nu$ | $\mu\nu$ |
|--------------------------|-------------|-----------|
| $W \rightarrow \ell\nu$ | 14.2±0.5 | 11.2±0.5 |
| $Z \rightarrow \ell\ell$ | 0.022±0.001 | 0.76±0.01 |
| diboson | 1.2±0.2 | 0.71±0.15 |
| $t\bar{t}$ | 0.24±0.11 | 0.09±0.05 |
| QCD | 0.8±0.3 | – |
| Total | 16.5±0.6 | 12.8±0.5 |

($\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) around the electron track, and the requirement is $\sum E_T < 9$ GeV, where the sum includes all calorimeter energy clusters in the cone excluding the core energy deposited by the electron. The sum is corrected to account for additional interactions and leakage of the electron energy outside this core. In the muon channel, the isolation energy is measured using inner detector tracks with $p_T^{\text{trk}} > 1$ GeV in a cone $\Delta R < 0.3$ around the muon track. The isolation requirement is $\sum p_T^{\text{trk}} < 0.05 p_T$, where the muon track is excluded from the sum. The scaling of the threshold with the muon p_T reduces efficiency losses due to radiation from the muon at high p_T .

Missing E_T thresholds are imposed to further suppress the background from QCD and W +jets (events where the SM W recoils against hadronic jets). In both channels, the threshold used for the charged lepton p_T is also applied to the missing E_T : $E_T^{\text{miss}} > 85$ GeV for the electron channel and $E_T^{\text{miss}} > 25$ GeV for the muon channel.

The above constitute the event preselection requirements. An m_T threshold varying with W' or W^* mass and decay channel is applied after preselection to establish the final event counts.

In the electron channel, the QCD background is estimated from data using the *ABCD* technique [33] with the isolation energy and missing E_T serving as discriminants. Consistent results are obtained using the *inverted isolation* technique described in Ref. [3].

The QCD background for the muon channel is evaluated using the *matrix method* [31]. This background is less than 1 % of the total background, and so it is neglected in the following.

The same reconstruction and event selection are applied to both data and simulated samples. Figure 2 shows the charged lepton p_T , missing E_T , and m_T spectra for events with $m_T > 200$ GeV in each channel after event preselection. The data, the expected background, and three examples of W' signals at different masses are shown. The m_T threshold, which is below that used in all of the final selections, discriminates against the W +jets and QCD backgrounds.

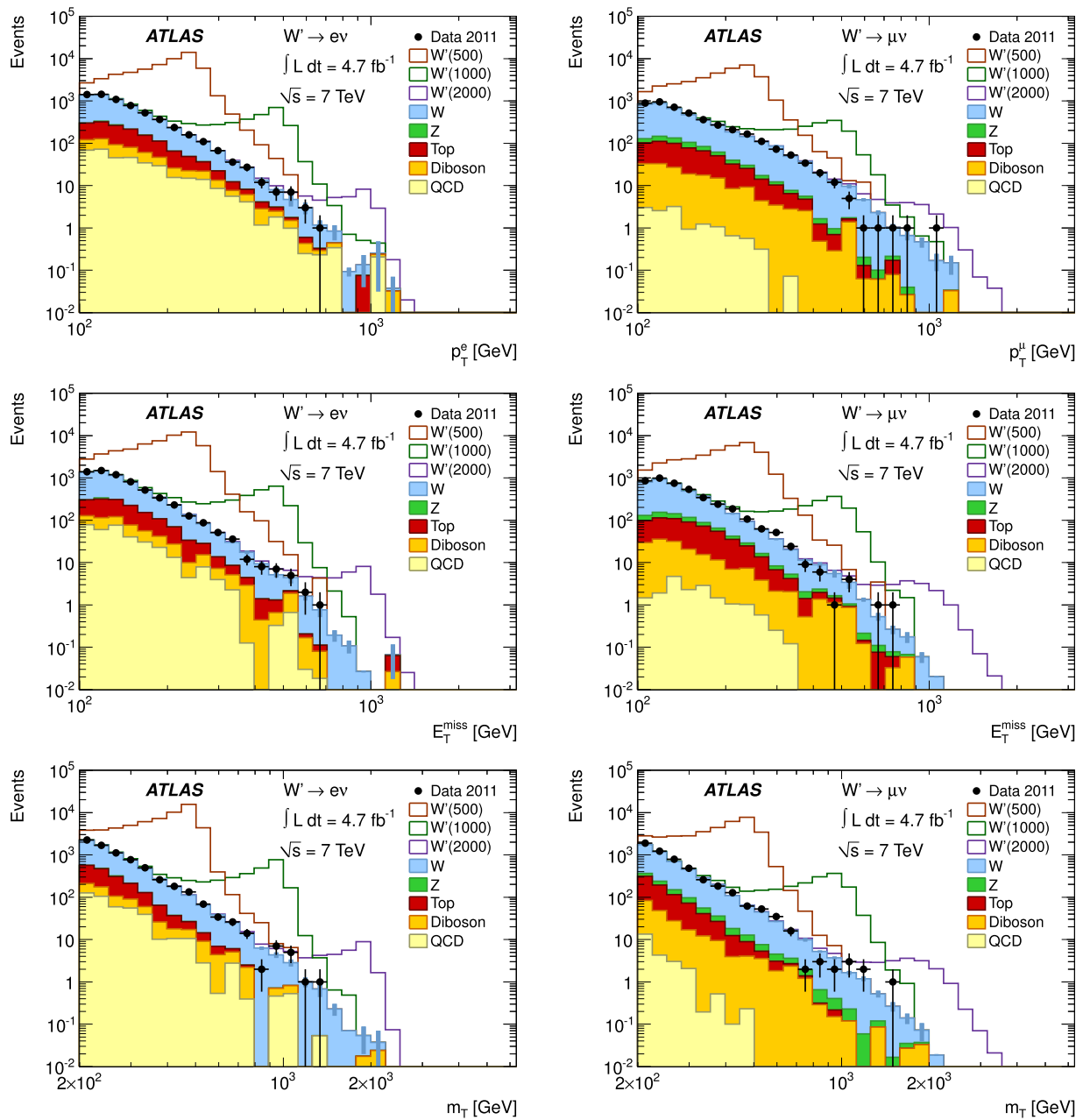


Fig. 2 Spectra of charged lepton p_T (top), missing E_T (center) and m_T (bottom) for the electron (left) and muon (right) channels for events with $m_T > 200$ GeV after event preselection. The points represent data and the filled histograms show the stacked backgrounds. Open histograms are $W' \rightarrow \ell\nu$ signals added to the background with masses in GeV indicated in parentheses in the legend. The QCD backgrounds

estimated from data are also shown. The signal and other background samples are normalised using the integrated luminosity of the data and the NNLO (approximate-NNLO for $t\bar{t}$) cross sections listed in Table 1. The error bars on the data and background sums are statistical, i.e. the latter do not include the systematic uncertainties used in the statistical analysis

The m_T spectra for the data and expected background are consistent within statistical and systematic uncertainties.

Table 2 shows the contributions to the background for $m_T > 794$ GeV, the region used to search for a W' with a mass of 1000 GeV. The $W \rightarrow \ell\nu$ background dominates and the background for the electron channel is higher than that for muons because of the difference in acceptance.

5 Statistical analysis and systematics

Discovery significance and σB limits are evaluated independently for W' and W^* following the same procedure as for the previous analysis [4]. The observed number of events N_{obs} is the count after final selection including the requirement $m_T > m_{T,\text{min}}$, with that threshold chosen sepa-

Table 3 Event selection efficiencies for the $W' \rightarrow e\nu$ and $W' \rightarrow \mu\nu$ searches. The first three columns are the W' mass, m_T threshold and decay channel. The next two are the signal selection efficiency, ε_{sig} , and the prediction for the number of signal events, N_{sig} , obtained with this efficiency. The uncertainty on N_{sig} includes contributions from the uncertainty on the cross sections but not from that on the integrated luminosity

| $m_{W'}$ [GeV] | $m_{T_{\min}}$ [GeV] | | ε_{sig} | N_{sig} |
|----------------|----------------------|----------|----------------------------|--------------------|
| 300 | 251 | $e\nu$ | 0.288 ± 0.023 | 176000 ± 19000 |
| | | $\mu\nu$ | 0.186 ± 0.016 | 114000 ± 13000 |
| 400 | 355 | $e\nu$ | 0.237 ± 0.023 | 46200 ± 5600 |
| | | $\mu\nu$ | 0.153 ± 0.018 | 30000 ± 4100 |
| 500 | 447 | $e\nu$ | 0.237 ± 0.023 | 19200 ± 2300 |
| | | $\mu\nu$ | 0.145 ± 0.019 | 11700 ± 1800 |
| 600 | 501 | $e\nu$ | 0.307 ± 0.024 | 11900 ± 1300 |
| | | $\mu\nu$ | 0.195 ± 0.017 | 7600 ± 900 |
| 750 | 631 | $e\nu$ | 0.297 ± 0.023 | 4470 ± 470 |
| | | $\mu\nu$ | 0.189 ± 0.016 | 2840 ± 320 |
| 1000 | 794 | $e\nu$ | 0.339 ± 0.023 | 1330 ± 130 |
| | | $\mu\nu$ | 0.223 ± 0.015 | 877 ± 90 |
| 1250 | 1000 | $e\nu$ | 0.323 ± 0.024 | 395 ± 47 |
| | | $\mu\nu$ | 0.212 ± 0.019 | 259 ± 34 |
| 1500 | 1122 | $e\nu$ | 0.351 ± 0.026 | 146 ± 20 |
| | | $\mu\nu$ | 0.237 ± 0.021 | 99 ± 14 |
| 1750 | 1413 | $e\nu$ | 0.280 ± 0.024 | 42.7 ± 6.8 |
| | | $\mu\nu$ | 0.179 ± 0.024 | 27.3 ± 5.2 |
| 2000 | 1413 | $e\nu$ | 0.317 ± 0.025 | 18.8 ± 3.2 |
| | | $\mu\nu$ | 0.215 ± 0.022 | 12.7 ± 2.3 |
| 2250 | 1413 | $e\nu$ | 0.315 ± 0.022 | 7.8 ± 1.5 |
| | | $\mu\nu$ | 0.218 ± 0.017 | 5.4 ± 1.0 |
| 2500 | 1413 | $e\nu$ | 0.276 ± 0.024 | 3.1 ± 1.4 |
| | | $\mu\nu$ | 0.184 ± 0.024 | 2.0 ± 1.0 |
| 2750 | 1413 | $e\nu$ | 0.217 ± 0.020 | 1.18 ± 0.59 |
| | | $\mu\nu$ | 0.149 ± 0.020 | 0.81 ± 0.41 |
| 3000 | 1413 | $e\nu$ | 0.143 ± 0.027 | 0.43 ± 0.25 |
| | | $\mu\nu$ | 0.106 ± 0.031 | 0.32 ± 0.20 |

rately for each mass and decay channel to maximize sensitivity. A Bayesian posterior probability distribution for the signal σB is evaluated with a Poisson likelihood at each mass for each decay channel and for the combination of the two channels. A positive, flat prior is used for the signal σB , and Gaussian distributions are used for the three nuisance parameters: ε_{sig} , the efficiency to select signal events, N_{bg} , the expected number of background events and L_{int} , the integrated luminosity. For each observed posterior, an ensemble of expected posteriors is generated assuming no signal and the same prior distributions for N_{bg} and L_{int} .

Each of the observed posteriors is used to evaluate an observed limit on σB , and the ensemble of expected posteriors provides the corresponding expected limit distribution. All

Table 4 Event selection efficiencies for the $W^* \rightarrow e\nu$ and $W^* \rightarrow \mu\nu$ searches. The first three columns are the W^* mass, m_T threshold and decay channel. The next two are the signal selection efficiency, ε_{sig} , and the prediction for the number of signal events, N_{sig} , obtained with this efficiency. The uncertainty on N_{sig} includes contributions from the uncertainty on the cross sections but not from that on the integrated luminosity

| m_{W^*} [GeV] | $m_{T_{\min}}$ [GeV] | | ε_{sig} | N_{sig} |
|-----------------|----------------------|----------|----------------------------|-------------------|
| 400 | 316 | $e\nu$ | 0.189 ± 0.021 | 26300 ± 3200 |
| | | $\mu\nu$ | 0.118 ± 0.020 | 16400 ± 2900 |
| 500 | 398 | $e\nu$ | 0.182 ± 0.020 | 10800 ± 1300 |
| | | $\mu\nu$ | 0.114 ± 0.021 | 6740 ± 1300 |
| 750 | 562 | $e\nu$ | 0.224 ± 0.021 | 2460 ± 270 |
| | | $\mu\nu$ | 0.143 ± 0.019 | 1570 ± 230 |
| 1000 | 708 | $e\nu$ | 0.267 ± 0.022 | 766 ± 83 |
| | | $\mu\nu$ | 0.172 ± 0.017 | 493 ± 60 |
| 1250 | 891 | $e\nu$ | 0.254 ± 0.021 | 225 ± 26 |
| | | $\mu\nu$ | 0.216 ± 0.015 | 192 ± 21 |
| 1500 | 1122 | $e\nu$ | 0.212 ± 0.021 | 63.5 ± 9.0 |
| | | $\mu\nu$ | 0.192 ± 0.016 | 57.5 ± 7.5 |
| 1750 | 1122 | $e\nu$ | 0.330 ± 0.023 | 35.0 ± 5.0 |
| | | $\mu\nu$ | 0.208 ± 0.016 | 22.1 ± 3.2 |
| 2000 | 1413 | $e\nu$ | 0.258 ± 0.021 | 9.9 ± 1.7 |
| | | $\mu\nu$ | 0.156 ± 0.018 | 6.0 ± 1.2 |
| 2250 | 1413 | $e\nu$ | 0.338 ± 0.024 | 4.8 ± 1.0 |
| | | $\mu\nu$ | 0.211 ± 0.016 | 2.97 ± 0.63 |
| 2500 | 1413 | $e\nu$ | 0.397 ± 0.025 | 2.03 ± 0.53 |
| | | $\mu\nu$ | 0.241 ± 0.016 | 1.23 ± 0.32 |
| 2750 | 1413 | $e\nu$ | 0.449 ± 0.027 | 0.83 ± 0.28 |
| | | $\mu\nu$ | 0.260 ± 0.016 | 0.48 ± 0.16 |
| 3000 | 1413 | $e\nu$ | 0.475 ± 0.029 | 0.31 ± 0.13 |
| | | $\mu\nu$ | 0.276 ± 0.016 | 0.179 ± 0.077 |

limits are at 95 % CL (credibility level). Discovery significance is assessed from the fraction of the expected posteriors that are more signal-like than the observation.

The values and uncertainties for ε_{sig} are presented in Tables 3 and 4, and those for N_{bg} and N_{obs} in Table 5. The ε_{sig} tables also give the predicted numbers of signal events, N_{sig} , with their uncertainties accounting for the uncertainties in both ε_{sig} and the cross-section calculations.

The maximum value for the $W' \rightarrow \ell\nu$ signal selection efficiency is at $m_{W'} = 1500$ GeV. For lower masses, the efficiency falls because the relative m_T threshold, $m_{T_{\min}}/m_{W'}$, is increased to reduce the background level. For higher masses, the efficiency falls because a large fraction of the cross section goes via off-shell production with $m_{\ell\nu} \ll m_{W'}$. This effect is not seen for $W^* \rightarrow \ell\nu$ because its derivative couplings [6] suppress off-shell production at low mass.

The fraction of fully simulated signal events that pass the event selection and are above the m_T threshold provides the initial estimate of ε_{sig} for each channel and mass. For W' ,

Table 5 Background levels and observed counts for the $W' \rightarrow \ell\nu$ and $W^* \rightarrow \ell\nu$ searches in both the electron and muon channels. The first two columns are the m_T threshold and decay channel, followed by the expected number of background events, N_{bg} , and the number of events observed in data, N_{obs} . The uncertainty on N_{bg} includes contributions from the uncertainties on the cross sections but not from that on the integrated luminosity

| $m_{T_{min}}$ [GeV] | | N_{bg} | N_{obs} |
|---------------------|----------|-----------------|-----------|
| 251 | $e\nu$ | 3190 ± 260 | 3105 |
| | $\mu\nu$ | 1950 ± 190 | 2023 |
| 316 | $e\nu$ | 1240 ± 100 | 1229 |
| | $\mu\nu$ | 773 ± 72 | 750 |
| 355 | $e\nu$ | 761 ± 64 | 734 |
| | $\mu\nu$ | 492 ± 44 | 491 |
| 398 | $e\nu$ | 467 ± 39 | 474 |
| | $\mu\nu$ | 285 ± 26 | 307 |
| 447 | $e\nu$ | 277 ± 24 | 293 |
| | $\mu\nu$ | 178 ± 15 | 179 |
| 501 | $e\nu$ | 164 ± 14 | 159 |
| | $\mu\nu$ | 113 ± 10 | 117 |
| 562 | $e\nu$ | 95.8 ± 8.4 | 90 |
| | $\mu\nu$ | 66.2 ± 5.8 | 64 |
| 631 | $e\nu$ | 54.5 ± 5.2 | 56 |
| | $\mu\nu$ | 40.0 ± 3.7 | 29 |
| 708 | $e\nu$ | 30.7 ± 3.0 | 30 |
| | $\mu\nu$ | 22.7 ± 2.2 | 13 |
| 794 | $e\nu$ | 16.5 ± 1.7 | 16 |
| | $\mu\nu$ | 12.8 ± 1.4 | 11 |
| 891 | $e\nu$ | 9.0 ± 1.0 | 14 |
| 1000 | $e\nu$ | 5.15 ± 0.69 | 7 |
| | $\mu\nu$ | 3.86 ± 0.58 | 6 |
| 1122 | $e\nu$ | 2.57 ± 0.42 | 2 |
| | $\mu\nu$ | 2.21 ± 0.34 | 3 |
| 1413 | $e\nu$ | 0.64 ± 0.18 | 0 |
| | $\mu\nu$ | 0.51 ± 0.12 | 1 |

small corrections are then made to account for the difference in acceptance at NNLO (obtained from FEWZ) and that in the LO simulation. These vary from a 10 % increase for $m_{W'} = 500$ GeV to an 11 % decrease for $m_{W'} = 2500$ GeV. Contributions from $W' \rightarrow \tau\nu$ with the τ -lepton decaying leptonically have been neglected. These would increase the W' signal strength by 3–4 % for the highest masses. The background level is estimated for each mass by summing the EW and $t\bar{t}$ event counts from simulation, and adding the small QCD contribution in the electron channel.

The uncertainties on ϵ_{sig} , N_{bg} and L_{int} account for experimental and theoretical systematic effects as well as the statistics of the simulation samples. The uncertainty on L_{int} is included separately to allow for the correlation between signal and background. The experimental systematic uncer-

Table 6 Relative uncertainties on the event selection efficiency and background level for a W' with a mass of 1500 GeV. The efficiency uncertainties include contributions from the trigger, reconstruction and event selection. The cross-section uncertainty for ϵ_{sig} is that assigned to the acceptance correction described in the text. The cross-section uncertainty on N_{bg} is that from the cross-section calculations. The last row gives the total uncertainties

| Source | ϵ_{sig} | | N_{bg} | |
|-----------------------------|------------------|----------|----------|----------|
| | $e\nu$ | $\mu\nu$ | $e\nu$ | $\mu\nu$ |
| Efficiency | 5 % | 2 % | 4 % | 2 % |
| Energy/momentum resolution | – | 1 % | 3 % | – |
| Energy/momentum scale | 2 % | – | 4 % | – |
| Missing E_T | – | – | 2 % | 4 % |
| QCD background | – | – | 4 % | – |
| Monte Carlo statistics | 5 % | 9 % | 10 % | 9 % |
| Cross section (shape/level) | 3 % | 3 % | 12 % | 12 % |
| Total | 7 % | 9 % | 17 % | 16 % |

tainties include efficiencies for the electron or muon trigger, reconstruction and selection. Lepton momentum and missing E_T response, characterised by scale and resolution, are also included. Most of these performance metrics are measured at relatively low p_T and their values are extrapolated to the high- p_T regime relevant to this analysis. The uncertainties in these extrapolations are included but their contributions are small compared to the total uncertainty on ϵ_{sig} or N_{bg} . The uncertainty on the QCD background estimate also contributes to the background-level uncertainties for the electron channel. Theoretical uncertainties include those from the cross-section calculations (see Sect. 3) and from the W' acceptance corrections. The values for the uncertainties are similar to those obtained in the previous analysis. Table 6 summarizes the uncertainties on the event selection efficiencies and background levels for the $W' \rightarrow \ell\nu$ signal with $m_{W'} = 1500$ GeV using $m_T > 1122$ GeV.

6 Results

None of the observations for any mass point in either channel or their combination shows an excess with significance above three sigma, so there is no evidence for the observation of $W' \rightarrow \ell\nu$ or $W^* \rightarrow \ell\nu$. Tables 7 and 8 and Fig. 3 present the 95 % CL observed limits on σB for both $W' \rightarrow \ell\nu$ and $W^* \rightarrow \ell\nu$ in the electron channel, the muon channel and their combination. The tables also give the limits obtained without systematic uncertainties and with various subsets. The uncertainties on the signal efficiency have very little effect on the final limits, and the background-level and luminosity uncertainties are important only for the lowest masses. The figure also shows the expected limits and the

Table 7 Observed upper limits on σB for $W' \rightarrow e\nu$, $W' \rightarrow \mu\nu$ and the combination of the two. The first two columns are the W' mass and decay channel. The following columns are the 95 % CL limits with headers indicating the nuisance parameters for which uncertainties are included: S for the event selection efficiency (ε_{sig}), B for the background level (N_{bg}), and L for the integrated luminosity (L_{int}). These values neglect correlations between the two channels for the combined limit. The only important correlation, that from the background cross section, is included in the column SB_{cL} . The last column in each row (SBL for e and μ and SB_{cL} for $e\mu$) is the final limit (including all systematic uncertainties) for the mass listed in the first column. These are the limits shown in Fig. 3 (left)

| $m_{W'}$ [GeV] | | 95 % CL limit on σB [fb] | | | | |
|----------------|--------|----------------------------------|-----|-----|-----|-------------------------|
| | | none | S | SB | SBL | SB_{cL} |
| 300 | e | 50 | 51 | 356 | 500 | |
| | μ | 173 | 179 | 514 | 557 | |
| | $e\mu$ | 61 | 62 | 295 | 329 | 389 |
| 400 | e | 36 | 37 | 111 | 124 | |
| | μ | 62 | 65 | 140 | 153 | |
| | $e\mu$ | 30 | 30 | 84 | 92 | 110 |
| 500 | e | 43 | 44 | 65 | 70 | |
| | μ | 42 | 44 | 64 | 69 | |
| | $e\mu$ | 32 | 32 | 47 | 50 | 56 |
| 600 | e | 16 | 17 | 25 | 27 | |
| | μ | 28 | 29 | 36 | 39 | |
| | $e\mu$ | 14 | 14 | 21 | 22 | 24 |
| 750 | e | 12 | 13 | 15 | 15 | |
| | μ | 9.0 | 9.2 | 11 | 11 | |
| | $e\mu$ | 6.8 | 6.8 | 8.1 | 8.4 | 9.2 |
| 1000 | e | 5.6 | 6.0 | 6.3 | 6.5 | |
| | μ | 7.1 | 7.2 | 7.5 | 7.7 | |
| | $e\mu$ | 4.1 | 4.1 | 4.4 | 4.4 | 4.6 |
| 1250 | e | 5.5 | 5.5 | 5.6 | 5.7 | |
| | μ | 8.2 | 8.4 | 8.5 | 8.6 | |
| | $e\mu$ | 4.7 | 4.7 | 4.8 | 4.9 | 4.9 |
| 1500 | e | 2.8 | 2.8 | 2.9 | 2.9 | |
| | μ | 5.2 | 5.4 | 5.4 | 5.4 | |
| | $e\mu$ | 2.3 | 2.3 | 2.3 | 2.4 | 2.4 |
| 1750 | e | 2.3 | 2.3 | 2.3 | 2.3 | |
| | μ | 5.2 | 5.5 | 5.5 | 5.5 | |
| | $e\mu$ | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |
| 2000 | e | 2.0 | 2.0 | 2.0 | 2.1 | |
| | μ | 4.3 | 4.4 | 4.5 | 4.5 | |
| | $e\mu$ | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| 2250 | e | 2.0 | 2.1 | 2.1 | 2.1 | |
| | μ | 4.2 | 4.3 | 4.3 | 4.4 | |
| | $e\mu$ | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| 2500 | e | 2.3 | 2.4 | 2.4 | 2.4 | |
| | μ | 5.0 | 5.3 | 5.3 | 5.3 | |
| | $e\mu$ | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |
| 2750 | e | 2.9 | 3.0 | 3.0 | 3.0 | |
| | μ | 6.2 | 6.6 | 6.6 | 6.7 | |
| | $e\mu$ | 2.3 | 2.4 | 2.4 | 2.4 | 2.4 |

Table 7 (Continued)

| $m_{W'}$ [GeV] | | 95 % CL limit on σB [fb] | | | | |
|----------------|--------|----------------------------------|-----|-----|-----|-------------------------|
| | | none | S | SB | SBL | SB_{cL} |
| 3000 | e | 4.5 | 5.0 | 5.0 | 5.0 | |
| | μ | 8.7 | 15 | 15 | 15 | |
| | $e\mu$ | 3.5 | 3.7 | 3.7 | 3.7 | 3.7 |

Table 8 Observed upper limits on σB for $W^* \rightarrow e\nu$, $W^* \rightarrow \mu\nu$ and the combination of the two. The columns are as for Table 7. The final (rightmost) limits are shown in Fig. 3 (right)

| m_{W^*} [GeV] | | 95 % CL limit on σB [fb] | | | | |
|-----------------|--------|----------------------------------|-----|-----|-----|-------------------------|
| | | none | S | SB | SBL | SB_{cL} |
| 400 | e | 68 | 71 | 236 | 264 | |
| | μ | 68 | 75 | 263 | 289 | |
| | $e\mu$ | 47 | 48 | 167 | 186 | 222 |
| 500 | e | 57 | 60 | 114 | 125 | |
| | μ | 93 | 106 | 160 | 171 | |
| | $e\mu$ | 57 | 58 | 96 | 104 | 116 |
| 750 | e | 16 | 17 | 22 | 24 | |
| | μ | 23 | 25 | 30 | 31 | |
| | $e\mu$ | 13 | 13 | 17 | 18 | 19 |
| 1000 | e | 10 | 10 | 11 | 11 | |
| | μ | 7.0 | 7.2 | 7.8 | 8.1 | |
| | $e\mu$ | 5.0 | 5.1 | 5.6 | 5.8 | 6.2 |
| 1250 | e | 11 | 11 | 11 | 11 | |
| | μ | 7.3 | 7.4 | 7.8 | 7.9 | |
| | $e\mu$ | 6.7 | 6.7 | 6.9 | 7.0 | 7.2 |
| 1500 | e | 4.6 | 4.7 | 4.8 | 4.8 | |
| | μ | 9.0 | 9.2 | 9.3 | 9.4 | |
| | $e\mu$ | 4.2 | 4.3 | 4.3 | 4.3 | 4.4 |
| 1750 | e | 3.0 | 3.0 | 3.0 | 3.0 | |
| | μ | 6.0 | 6.1 | 6.1 | 6.2 | |
| | $e\mu$ | 2.5 | 2.5 | 2.6 | 2.6 | 2.6 |
| 2000 | e | 2.5 | 2.5 | 2.5 | 2.5 | |
| | μ | 5.9 | 6.2 | 6.2 | 6.2 | |
| | $e\mu$ | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| 2250 | e | 1.9 | 1.9 | 1.9 | 1.9 | |
| | μ | 4.4 | 4.5 | 4.5 | 4.5 | |
| | $e\mu$ | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| 2500 | e | 1.5 | 1.5 | 1.5 | 1.5 | |
| | μ | 3.8 | 3.9 | 3.9 | 3.9 | |
| | $e\mu$ | 1.3 | 1.3 | 1.3 | 1.4 | 1.4 |
| 2750 | e | 1.4 | 1.4 | 1.4 | 1.4 | |
| | μ | 3.6 | 3.6 | 3.6 | 3.6 | |
| | $e\mu$ | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| 3000 | e | 1.3 | 1.4 | 1.4 | 1.4 | |
| | μ | 3.4 | 3.4 | 3.4 | 3.4 | |
| | $e\mu$ | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |

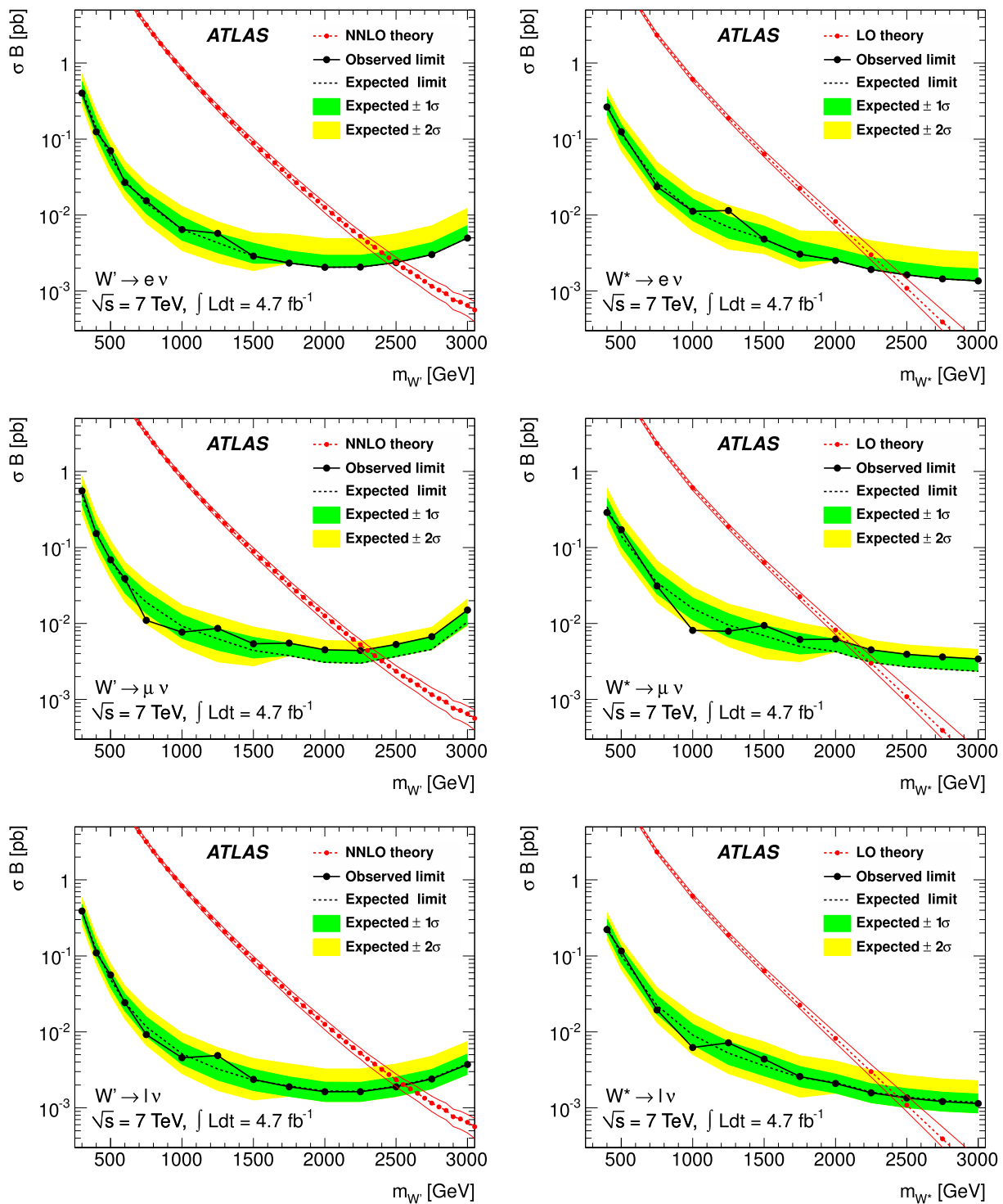


Fig. 3 Expected and observed limits on σB for $W' \rightarrow \ell \nu$ (left) and $W^* \rightarrow \ell \nu$ (right) in the electron channel (top), muon channel (center) and combined (bottom) assuming the same branching fraction for both

channels. The calculated values for σB (NNLO for W' and LO for W^*) and their uncertainties are also shown

theoretical σB for an SSM W' and for a W^* with quark and gluon coupling strengths normalised to reproduce the W' width.

The intersection between the central theoretical prediction and the observed limits provides the 95 % CL lower limits on the mass. Table 9 presents the expected and ob-

Table 9 W' and W^* mass limits for the electron and muon decay channels and their combination. The first column is the decay channel and the following give the expected (Exp.) and observed (Obs.) mass limits for the SSM W' and for the W^* with equivalent couplings (i.e. chosen to produce the same decay width as the SSM W'). Masses below the reported limit are excluded by this search

| | Mass limit [TeV] | | | |
|--------|------------------|------|-------|------|
| | W' | | W^* | |
| | Exp. | Obs. | Exp. | Obs. |
| e | 2.50 | 2.50 | 2.38 | 2.38 |
| μ | 2.38 | 2.28 | 2.25 | 2.09 |
| $e\mu$ | 2.55 | 2.55 | 2.42 | 2.42 |

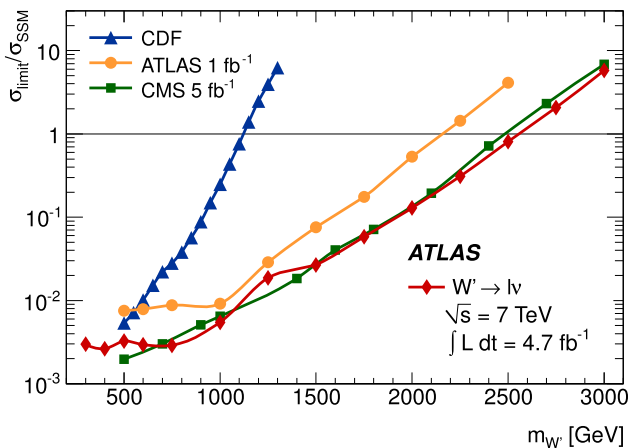


Fig. 4 Normalised cross-section limits ($\sigma_{\text{limit}}/\sigma_{\text{SSM}}$) for $W' \rightarrow \ell \nu$ as a function of mass for this measurement and from CDF, CMS and the previous ATLAS search. The cross-section calculations assume the W' has the same couplings as the SM W boson. The region above each curve is excluded at the 95 % CL

served W' and W^* mass limits for the electron and muon decay channels and their combination.

The limits presented here are a significant improvement over those reported in previous ATLAS analyses. Figure 4 shows the new and previous ATLAS σB limits for $W' \rightarrow \ell \nu$ along with the most recent results from CMS [2] and CDF [1]. Compared with the previous ATLAS results, the limits presented here cover a wider mass range and are about a factor of five lower at the upper end of the range where they overlap. Limits from CMS based on data from the same LHC run period are similar.

7 Conclusions

The ATLAS detector has been used to search for new high-mass states decaying to a lepton plus missing E_T in pp collisions at $\sqrt{s} = 7$ TeV using 4.7 fb^{-1} of integrated luminosity. No excess beyond SM expectations is observed. Bayesian limits on σB are shown in Figs. 3 and 4. A W' with SSM

couplings is excluded for $m_{W'} < 2.55$ TeV at the 95 % CL and a W^* with equivalent couplings for $m_{W^*} < 2.42$ TeV.

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The ATLAS Collaboration

G. Aad⁴⁸, T. Abajyan²¹, B. Abbott¹¹¹, J. Abdallah¹², S. Abdel Khalek¹¹⁵, A.A. Abdelalim⁴⁹, O. Abidinov¹¹, R. Aben¹⁰⁵, B. Abi¹¹², M. Abolins⁸⁸, O.S. AbouZeid¹⁵⁸, H. Abramowicz¹⁵³, H. Abreu¹³⁶, B.S. Acharya^{164a,164b}, L. Adamczyk³⁸, D.L. Adams²⁵, T.N. Addy⁵⁶, J. Adelman¹⁷⁶, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²³, J.A. Aguilar-Saavedra^{124b,a}, M. Agustoni¹⁷, M. Aharrouche⁸¹, S.P. Ahlen²², F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴¹, G. Aielli^{133a,133b}, T. Akdogan^{19a}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, M.S. Alam², M.A. Alam⁷⁶, J. Albert¹⁶⁹, S. Albrand⁵⁵, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, F. Alessandria^{89a}, C. Alexa^{26a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos¹⁰, M. Alhroob^{164a,164c}, M. Aliev¹⁶, G. Alimonti^{89a}, J. Alison¹²⁰, B.M.M. Allbrooke¹⁸, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷², A. Alonso⁷⁹, F. Alonso⁷⁰, A. Altheimer³⁵, B. Alvarez Gonzalez⁸⁸, M.G. Alviggi^{102a,102b}, K. Amako⁶⁵, C. Amelung²³, V.V. Ammosov^{128,*}, S.P. Amor Dos Santos^{124a}, A. Amorim^{124a,b}, N. Amram¹⁵³, C. Anastopoulos³⁰, L.S. Ancu¹⁷, N. Andari¹¹⁵, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders^{58a}, K.J. Anderson³¹, A. Andreazza^{89a,89b}, V. Andrei^{58a}, M-L. Andrieux⁵⁵, X.S. Anduaga⁷⁰, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A. Anisenkov¹⁰⁷, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁶, J. Antos^{144b}, F. Anulli^{132a}, M. Aoki¹⁰¹, S. Aoun⁸³, L. Aperio Bella⁵, R. Apolle^{118,c}, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁵, A.T.H. Arce⁴⁵, S. Arfaoui¹⁴⁸, J-F. Arguin¹⁵, E. Arik^{19a,*}, M. Arik^{19a}, A.J. Armbruster⁸⁷, O. Arnaez⁸¹, V. Arnal⁸⁰, C. Arnault¹¹⁵, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²¹, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷³, S. Ask²⁸, B. Åsman^{146a,146b}, L. Asquith⁶, K. Assamagan²⁵, A. Astbury¹⁶⁹, M. Atkinson¹⁶⁵, B. Aubert⁵, E. Auge¹¹⁵, K. Augsten¹²⁷, M. Aurousseau^{145a}, G. Avolio¹⁶³, R. Avramidou¹⁰, D. Axen¹⁶⁸, G. Azuelos^{93,d}, Y. Azuma¹⁵⁵, M.A. Baak³⁰, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁵, H. Bachacou¹³⁶, K. Bachas³⁰, M. Backes⁴⁹, M. Backhaus²¹, E. Badescu^{26a}, P. Bagnaia^{132a,132b}, S. Bahini-pati³, Y. Bai^{33a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸, J.T. Baines¹²⁹, O.K. Baker¹⁷⁶, M.D. Baker²⁵, S. Baker⁷⁷, E. Banas³⁹, P. Banerjee⁹³, Sw. Banerjee¹⁷³, D. Banfi³⁰, A. Bangert¹⁵⁰, V. Bansal¹⁶⁹, H.S. Bansil¹⁸, L. Barak¹⁷², S.P. Baranov⁹⁴, A. Barbaro Galtieri¹⁵, T. Barber⁴⁸, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²¹, D.Y. Bardin⁶⁴, T. Barillari⁹⁹, M. Barisonzi¹⁷⁵, T. Barklow¹⁴³, N. Barlow²⁸, B.M. Barnett¹²⁹, R.M. Barnett¹⁵, A. Baronecelli^{134a}, G. Barone⁴⁹, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁵, R. Bartoldus¹⁴³, A.E. Barton⁷¹, V. Bartsch¹⁴⁹, A. Basye¹⁶⁵, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁸, A. Battaglia¹⁷, M. Battistin³⁰, F. Bauer¹³⁶, H.S. Bawa^{143,e}, S. Beale⁹⁸, T. Beau⁷⁸, P.H. Beauchemin¹⁶¹, R. Beccherle^{50a}, P. Bechtel²¹, H.P. Beck¹⁷, A.K. Becker¹⁷⁵, S. Becker⁹⁸, M. Beckingham¹³⁸, K.H. Becks¹⁷⁵, A.J. Beddall^{19c}, A. Beddall^{19c}, S. Bedikian¹⁷⁶, V.A. Bednyakov⁶⁴, C.P. Bee⁸³, L.J. Beemster¹⁰⁵, M. Begel²⁵, S. Behar Harpaz¹⁵², P.K. Behara⁶², M. Beimforde⁹⁹, C. Belanger-Champagne⁸⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Belagamba^{20a}, F. Bellina³⁰, M. Bellomo³⁰, A. Belloni⁵⁷, O. Beloborodova^{107,f}, K. Belotskiy⁹⁶, O. Beltramello³⁰, O. Benary¹⁵³, D. Bencheikroun^{135a}, K. Bendtz^{146a,146b}, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, E. Benhar Noccioli⁴⁹, J.A. Benitez Garcia^{159b}, D.P. Benjamin⁴⁵, M. Benoit¹¹⁵, J.R. Bensinger²³, K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge³⁰, E. Bergeaas Kuutmann⁴², N. Berger⁵, F. Berghaus¹⁶⁹, E. Berglund¹⁰⁵, J. Beringer¹⁵, P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius²⁵, T. Berry⁷⁶, C. Bertella⁸³,

- A. Bertin^{20a,20b}, F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, G.J. Besjes¹⁰⁴, N. Besson¹³⁶, S. Bethke⁹⁹, W. Bhimji⁴⁶, R.M. Bianchi³⁰, M. Bianco^{72a,72b}, O. Biebel⁹⁸, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁵, M. Biglietti^{134a}, H. Bilokon⁴⁷, M. Bindi^{20a,20b}, S. Binet¹¹⁵, A. Bingul^{19c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁸, B. Bittner⁹⁹, K.M. Black²², R.E. Blair⁶, J.-B. Blanchard¹³⁶, G. Blanchot³⁰, T. Blazek^{144a}, I. Bloch⁴², C. Blocker²³, J. Blocki³⁹, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumen-schein⁵⁴, G.J. Bobbink¹⁰⁵, V.B. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁵, C.R. Boddy¹¹⁸, M. Boehler⁴⁸, J. Boek¹⁷⁵, N. Boelaert³⁶, J.A. Bogaerts³⁰, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Bohm^{146a}, J. Bohm¹²⁵, V. Boisvert⁷⁶, T. Bold³⁸, V. Boldea^{26a}, N.M. Bolnet¹³⁶, M. Bomben⁷⁸, M. Bona⁷⁵, M. Boonekamp¹³⁶, S. Bordini⁷⁸, C. Borer¹⁷, A. Borisov¹²⁸, G. Borissov⁷¹, I. Borjanovic^{13a}, M. Borri⁸², S. Borroni⁸⁷, V. Bortolotto^{134a,134b}, K. Bos¹⁰⁵, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁵, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁵, N. Bous-son⁸³, A. Boveia³¹, J. Boyd³⁰, I.R. Boyko⁶⁴, I. Bozovic-Jelisavcic^{13b}, J. Bracinik¹⁸, P. Branchini^{134a}, G.W. Brandenburg⁵⁷, A. Brandt⁸, G. Brandt¹¹⁸, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun^{175,*}, S.F. Brazzale^{164a,164c}, B. Brelief¹⁵⁸, J. Bremer³⁰, K. Brendlinger¹²⁰, R. Brenner¹⁶⁶, S. Bressler¹⁷², D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁸⁸, F. Broggi^{89a}, C. Bromberg⁸⁸, J. Bronner⁹⁹, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, G. Brown⁸², H. Brown⁸, P.A. Bruckman de Renstrom³⁹, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, T. Buanes¹⁴, Q. Buat⁵⁵, F. Bucci⁴⁹, J. Buchanan¹¹⁸, P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸, A.G. Buck-ley⁴⁶, S.I. Buda^{26a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, M.K. Bugge¹¹⁷, O. Bulekov⁹⁶, A.C. Bun-dock⁷³, M. Bunse⁴³, T. Buran¹¹⁷, H. Burckhart³⁰, S. Burdin⁷³, T. Burgess¹⁴, S. Burke¹²⁹, E. Busato³⁴, P. Bussey⁵³, C.P. Buszello¹⁶⁶, B. Butler¹⁴³, J.M. Butler²², C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁸, S. Cabrera Urbán¹⁶⁷, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{24a}, R. Caloi^{132a,132b}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro³⁴, P. Camarri^{133a,133b}, D. Cameron¹¹⁷, L.M. Caminada¹⁵, R. Caminal Ar-madans¹², S. Campana³⁰, M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli^{31,g}, A. Canepa^{159a}, J. Cantero⁸⁰, R. Cantrill⁷⁶, L. Capasso^{102a,102b}, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}, D. Capriotti⁹⁹, M. Capua^{37a,37b}, R. Caputo⁸¹, R. Cardarelli^{133a}, T. Carli³⁰, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron⁸⁵, S. Caron¹⁰⁴, E. Carquin^{32b}, G.D. Carrillo Mon-toya¹⁷³, A.A. Carter⁷⁵, J.R. Carter²⁸, J. Carvalho^{124a,h}, D. Casadei¹⁰⁸, M.P. Casado¹², M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez^{173,i}, E. Castaneda-Miranda¹⁷³, V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124a}, G. Cataldi^{72a}, P. Catas-tini⁵⁷, A. Catinaccio³⁰, J.R. Catmore³⁰, A. Cattai³⁰, G. Cattani^{133a,133b}, S. Caughron⁸⁸, V. Cavaliere¹⁶⁵, P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹², V. Cavasinni^{122a,122b}, F. Ceradini^{134a,134b}, A.S. Cerqueira^{24b}, A. Cerri³⁰, L. Cerrito⁷⁵, F. Cerutti⁴⁷, S.A. Cetin^{19b}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁶, I. Chalupkova¹²⁶, K. Chan³, P. Chang¹⁶⁵, B. Chapleau⁸⁵, J.D. Chapman²⁸, J.W. Chapman⁸⁷, E. Chareyre⁷⁸, D.G. Charlton¹⁸, V. Chavda⁸², C.A. Chavez Barajas³⁰, S. Cheatham⁸⁵, S. Chekanov⁶, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰⁴, C. Chen⁶³, H. Chen²⁵, S. Chen^{33c}, X. Chen¹⁷³, Y. Chen³⁵, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁵, E. Cheu⁷, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani^{51a,*}, J.T. Childers³⁰, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷, A. Chitan^{26a}, M.V. Chizhov⁶⁴, G. Choudalakis³¹, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromeck-Burckhart³⁰, M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca³⁴, V. Cindro⁷⁴, C. Ciocca^{20a,20b}, A. Ciochio¹⁵, M. Cirilli⁸⁷, P. Cirkovic^{13b}, Z.H. Citron¹⁷², M. Citterio^{89a}, M. Ciubancan^{26a}, A. Clark⁴⁹, P.J. Clark⁴⁶, R.N. Clarke¹⁵, W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coc-caro¹³⁸, J. Cochran⁶³, L. Coffey²³, J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, E. Cogneras¹⁷⁸, J. Colas⁵, S. Cole¹⁰⁶, A.P. Col-ijn¹⁰⁵, N.J. Collins¹⁸, C. Collins-Tooth⁵³, J. Collot⁵⁵, T. Colombo^{119a,119b}, G. Colon⁸⁴, P. Conde Muño^{124a}, E. Co-niavitis¹¹⁸, M.C. Conidi¹², S.M. Consonni^{89a,89b}, V. Consorti⁴⁸, S. Constantinescu^{26a}, C. Conta^{119a,119b}, G. Conti⁵⁷, F. Conventi^{102a,j}, M. Cooke¹⁵, B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁸, K. Copic¹⁵, T. Cornelissen¹⁷⁵, M. Corradi^{20a}, F. Corriveau^{85,k}, A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, D. Côté³⁰, L. Cour-neyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁸, B.E. Cox⁸², K. Cranmer¹⁰⁸, F. Crescioli^{122a,122b}, M. Cristinziani²¹, G. Crosetti^{37a,37b}, S. Crépe-Renaudin⁵⁵, C.-M. Cuciuc^{26a}, C. Cuenca Almenar¹⁷⁶, T. Cuhadar Donszelmann¹³⁹, M. Curatolo⁴⁷, C.J. Cur-tis¹⁸, C. Cuthbert¹⁵⁰, P. Cwetanski⁶⁰, H. Czirr¹⁴¹, P. Czodrowski⁴⁴, Z. Czyzula¹⁷⁶, S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio^{132a,132b}, M.J. Da Cunha Sargedass De Sousa^{124a}, C. Da Via⁸², W. Dabrowski³⁸, A. Dafinca¹¹⁸, T. Dai⁸⁷, C. Dal-lapiccola⁸⁴, M. Dam³⁶, M. Dameri^{50a,50b}, D.S. Damiani¹³⁷, H.O. Danielsson³⁰, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{26b}, J.A. Dassoulas⁴², W. Davey²¹, T. Davidek¹²⁶, N. Davidson⁸⁶, R. Davidson⁷¹, E. Davies^{118,c}, M. Davies⁹³, O. Davignon⁷⁸, A.R. Davison⁷⁷, Y. Davygora^{58a}, E. Dawe¹⁴², I. Dawson¹³⁹, R.K. Daya-Ishmukhametova²³, K. De⁸, R. de Asmundis^{102a}, S. De Castro^{20a,20b}, S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, C. De La Taille¹¹⁵, H. De la Torre⁸⁰, F. De Lorenzi⁶³, L. de Mora⁷¹, L. De Noij¹⁰⁵, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, G. De Zorzi^{132a,132b}, W.J. Dearnaley⁷¹, R. Debbe²⁵, C. Debenedetti⁴⁶, B. Dechenaux⁵⁵, D.V. De-dovich⁶⁴, J. Degenhardt¹²⁰, C. Del Papa^{164a,164c}, J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, T. Delemontex⁵⁵, M. Deliyergiyev⁷⁴, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Della Pietra^{102a,j}, D. della Volpe^{102a,102b}, M. Delmastro⁵, P.A. Delsart⁵⁵, C. Deluca¹⁰⁵,

S. Demers¹⁷⁶, M. Demichev⁶⁴, B. Demirköz^{12,1}, J. Deng¹⁶³, S.P. Denisov¹²⁸, D. Derendarz³⁹, J.E. Derkaoui^{135d}, F. Derue⁷⁸, P. Dervan⁷³, K. Desch²¹, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁰⁵, A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸, R. Dhulipudi^{25,m}, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵, A. Di Girolamo³⁰, B. Di Girolamo³⁰, S. Di Luise^{134a,134b}, A. Di Matia¹⁷³, B. Di Micco³⁰, R. Di Nardo⁴⁷, A. Di Simone^{133a,133b}, R. Di Sipio^{20a,20b}, M.A. Diaz^{32a}, E.B. Diehl⁸⁷, J. Dietrich⁴², T.A. Dietzsch^{58a}, S. Diglio⁸⁶, K. Dindar Yagci⁴⁰, J. Dingfelder²¹, F. Dinut^{26a}, C. Dionisi^{132a,132b}, P. Dita^{26a}, S. Dita^{26a}, F. Dittus³⁰, F. Djama⁸³, T. Djobava^{51b}, M.A.B. do Vale^{24c}, A. Do Valle Wemans^{124a,n}, T.K.O. Doan⁵, M. Dobbs⁸⁵, R. Dobinson^{30,*}, D. Dobos³⁰, E. Dobson^{30,o}, J. Dodd³⁵, C. Doglioni⁴⁹, T. Doherty⁵³, Y. Doi^{65,*}, J. Dolejsi¹²⁶, I. Dolenc⁷⁴, Z. Dolezal¹²⁶, B.A. Dolgoshein^{96,*}, T. Dohmae¹⁵⁵, M. Donadelli^{24d}, J. Donini³⁴, J. Dopke³⁰, A. Doria^{102a}, A. Dos Anjos¹⁷³, A. Dotti^{122a,122b}, M.T. Dova⁷⁰, A.D. Doxiadis¹⁰⁵, A.T. Doyle⁵³, N. Dressnandt¹²⁰, M. Dris¹⁰, J. Dubbert⁹⁹, S. Dube¹⁵, E. Duchovni¹⁷², G. Duckeck⁹⁸, D. Duda¹⁷⁵, A. Dudarev³⁰, F. Dudziak⁶³, M. Dührssen³⁰, I.P. Duerdoth⁸², L. Dufлот¹¹⁵, M-A. Dufour⁸⁵, L. Duguid⁷⁶, M. Dunford³⁰, H. Duran Yildiz^{4a}, R. Duxfield¹³⁹, M. Dwuznik³⁸, F. Dydak³⁰, M. Düren⁵², W.L. Ebenstein⁴⁵, J. Ebke⁹⁸, S. Eckweiler⁸¹, K. Edmonds⁸¹, W. Edson², C.A. Edwards⁷⁶, N.C. Edwards⁵³, W. Ehrenfeld⁴², T. Eifert¹⁴³, G. Eigen¹⁴, K. Einsweiler¹⁵, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi^{135c}, M. Ellert¹⁶⁶, S. Elles⁵, F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis³⁰, J. Elmsheuser⁹⁸, M. Elsing³⁰, D. Emeliyanov¹²⁹, R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶¹, J. Erdmann⁵⁴, A. Ereditato¹⁷, D. Eriksson^{146a}, J. Ernst², M. Ernst²⁵, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, H. Esch⁴³, C. Escobar¹²³, X. Espinal Curull¹², B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etievre¹³⁶, E. Etzion¹⁵³, D. Evangelakou⁵⁴, H. Evans⁶⁰, L. Fabbri^{20a,20b}, C. Fabre³⁰, R.M. Fakhrutdinov¹²⁸, S. Falciano^{132a}, Y. Fang¹⁷³, M. Fanti^{89a,89b}, A. Farbin⁸, A. Farilla^{134a}, J. Farley¹⁴⁸, T. Farooque¹⁵⁸, S. Farrell¹⁶³, S.M. Farrington¹⁷⁰, P. Farthouat³⁰, F. Fassi¹⁶⁷, P. Fassnacht³⁰, D. Fassoulitis⁹, B. Fatholahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵, S. Fazio^{37a,37b}, R. Febbraro³⁴, P. Federic^{144a}, O.L. Fedin¹²¹, W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸, L. Felgioni⁸³, D. Fellmann⁶, C. Feng^{33d}, E.J. Feng⁶, A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, W. Fernando⁶, S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴², A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³¹, F. Fiedler⁸¹, A. Filipčič⁷⁴, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹, M.C.N. Fiolhais^{124a,h}, L. Fiorini¹⁶⁷, A. Firan⁴⁰, G. Fischer⁴², M.J. Fisher¹⁰⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹, J. Fleckner⁸¹, P. Fleischmann¹⁷⁴, S. Fleischmann¹⁷⁵, T. Flick¹⁷⁵, A. Floderus⁷⁹, L.R. Flores Castillo¹⁷³, M.J. Flowerdew⁹⁹, T. Fonseca Martin¹⁷, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a}, D. Fournier¹¹⁵, A.J. Fowler⁴⁵, H. Fox⁷¹, P. Francavilla¹², M. Franchini^{20a,20b}, S. Franchino^{119a,119b}, D. Francis³⁰, T. Frank¹⁷², S. Franz³⁰, M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁸, C. Friedrich⁴², F. Friedrich⁴⁴, R. Froeschl³⁰, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa³⁰, B.G. Fulson¹⁴³, J. Fuster¹⁶⁷, C. Gabaldon³⁰, O. Gabizon¹⁷², T. Gadfort²⁵, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁸, B. Galhardo^{124a}, E.J. Gallas¹¹⁸, V. Gallo¹⁷, B.J. Gallop¹²⁹, P. Gallus¹²⁵, K.K. Gan¹⁰⁹, Y.S. Gao^{143,e}, A. Gaponenko¹⁵, F. Garbersen¹⁷⁶, M. Garcia-Sciveres¹⁵, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷, R.W. Gardner³¹, N. Garelli³⁰, H. Garitaonandia¹⁰⁵, V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{119a}, B. Gaur¹⁴¹, L. Gauthier¹³⁶, P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gece¹⁶⁸, C.N.P. Gee¹²⁹, D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²¹, K. Gellerstedt^{146a,146b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁶, P. Gerlach¹⁷⁵, A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135b}, N. Ghodbane³⁴, B. Giacobbe^{20a}, S. Giagu^{132a,132b}, V. Giakoumopoulou⁹, V. Giangiobbe¹², F. Gianotti³⁰, B. Gibbard²⁵, A. Gibson¹⁵⁸, S.M. Gibson³⁰, M. Gilchriese¹⁵, D. Gillberg²⁹, A.R. Gillman¹²⁹, D.M. Gingrich^{3,d}, J. Ginzburg¹⁵³, N. Giokaris⁹, M.P. Giordani^{164c}, R. Giordano^{102a,102b}, F.M. Giorgi¹⁶, P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, M. Giunta⁹³, P. Giusti^{20a}, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴², K.W. Glitz¹⁷⁵, G.L. Glonti⁶⁴, J.R. Goddard⁷⁵, J. Godfrey¹⁴², J. Godlewski³⁰, M. Goebel⁴², T. Göpfert⁴⁴, C. Goeringer⁸¹, C. Gössling⁴³, S. Goldfarb⁸⁷, T. Golling¹⁷⁶, A. Gomes^{124a,b}, L.S. Gomez Fajardo⁴², R. Gonçalves⁷⁶, J. Gonçalves Pinto Firmino Da Costa⁴², L. Gonella²¹, S. González de la Hoz¹⁶⁷, G. Gonzalez Parra¹², M.L. Gonzalez Silva²⁷, S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸, L. Goossens³⁰, P.A. Gorbounov⁹⁵, H.A. Gordon²⁵, I. Gorelov¹⁰³, G. Gorfine¹⁷⁵, B. Gorini³⁰, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁹, B. Gosdzik⁴², A.T. Goshaw⁶, M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁴, I. Gough Eschrich¹⁶³, M. Goughri^{135a}, D. Goujdami^{135c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸, C. Goy⁵, S. Gozpinar²³, I. Grabowska-Bold³⁸, P. Grafström^{20a,20b}, K-J. Grahn⁴², F. Grancagnolo^{72a}, S. Grancagnolo¹⁶, V. Grassi¹⁴⁸, V. Gratchev¹²¹, N. Grau³⁵, H.M. Gray³⁰, J.A. Gray¹⁴⁸, E. Graziani^{134a}, O.G. Grebenyuk¹²¹, T. Greenshaw⁷³, Z.D. Greenwood^{25,m}, K. Gregersen³⁶, I.M. Gregor⁴², P. Grenier¹⁴³, J. Griffiths⁸, N. Grigalashvili⁶⁴, A.A. Grillo¹³⁷, S. Grinstein¹², Ph. Gris³⁴, Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, E. Gross¹⁷², J. Grosse-Knetter⁵⁴, J. Groth-Jensen¹⁷², K. Grybel¹⁴¹, D. Guest¹⁷⁶, C. Guicheney³⁴, S. Guindon⁵⁴, U. Gul⁵³, H. Guler^{85,p}, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁵, P. Gutierrez¹¹¹, N. Guttman¹⁵³, O. Gutzwiller¹⁷³, C. Guyot¹³⁶, C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas³⁰, C. Haber¹⁵, H.K. Hadavand⁴⁰, D.R. Hadley¹⁸, P. Haefner²¹, F. Hahn³⁰, S. Haider³⁰, Z. Hajduk³⁹, H. Hakobyan¹⁷⁷, D. Hall¹¹⁸, J. Haller⁵⁴, K. Hamacher¹⁷⁵, P. Hamal¹¹³, K. Hamano⁸⁶, M. Hamer⁵⁴, A. Hamilton^{145b,q}, S. Hamilton¹⁶¹, L. Han^{33b}, K. Hanagaki¹¹⁶, K. Hanawa¹⁶⁰, M. Hance¹⁵, C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁶, J.B. Hansen³⁶, J.D. Hansen³⁶, P.H. Hansen³⁶, P. Hansson¹⁴³,

K. Hara¹⁶⁰, G.A. Hare¹³⁷, T. Harenberg¹⁷⁵, S. Harkusha⁹⁰, D. Harper⁸⁷, R.D. Harrington⁴⁶, O.M. Harris¹³⁸, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁵, A. Harvey⁵⁶, S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁸⁸, M. Havranek²¹, C.M. Hawkes¹⁸, R.J. Hawkins³⁰, A.D. Hawkins⁷⁹, T. Hayakawa⁶⁶, T. Hayashi¹⁶⁰, D. Hayden⁷⁶, C.P. Hays¹¹⁸, H.S. Hayward⁷³, S.J. Haywood¹²⁹, S.J. Head¹⁸, V. Hedberg⁷⁹, L. Heelan⁸, S. Heim⁸⁸, B. Heinemann¹⁵, S. Heisterkamp³⁶, L. Helary²², C. Heller⁹⁸, M. Heller³⁰, S. Hellman^{146a,146b}, D. Hellmich²¹, C. Helsens¹², R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs⁵⁴, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁵, C. Hensel⁵⁴, T. Henß¹⁷⁵, C.M. Hernandez⁸, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁶, G. Herten⁴⁸, R. Hertenberger⁹⁸, L. Hervas³⁰, G.G. Hesketh⁷⁷, N.P. Hesse¹⁰⁵, E. Higón-Rodríguez¹⁶⁷, J.C. Hill²⁸, K.H. Hiller⁴², S. Hillert²¹, S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴³, D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁸, N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker³⁰, M.R. Hoferkamp¹⁰³, J. Hoffman⁴⁰, D. Hoffmann⁸³, M. Hohlfield⁸¹, M. Holder¹⁴¹, S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸, T.M. Hong¹²⁰, L. Hooft van Huysduynen¹⁰⁸, S. Horner⁴⁸, J-Y. Hostachy⁵⁵, S. Hou¹⁵¹, A. Houtmada^{135a}, J. Howard¹¹⁸, J. Howarth⁸², I. Hristova¹⁶, J. Hrivnac¹¹⁵, T. Hryn'ova⁵, P.J. Hsu⁸¹, S.-C. Hsu¹⁵, D. Hu³⁵, Z. Hubacek¹²⁷, F. Hubaut⁸³, F. Huegging²¹, A. Huettmann⁴², T.B. Huffman¹¹⁸, E.W. Hughes³⁵, G. Hughes⁷¹, M. Huhtinen³⁰, M. Hurwitz¹⁵, U. Husemann⁴², N. Huseynov^{64,r}, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, M. Ibbotson⁸², I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, P. Iengo^{102a}, O. Igonkina¹⁰⁵, Y. Ikegami⁶⁵, M. Ikeno⁶⁵, D. Iliadis¹⁵⁴, N. Ilic¹⁵⁸, T. Ince²¹, J. Inigo-Golfin³⁰, P. Ioannou⁹, M. Iodice^{134a}, K. Iordanidou⁹, V. Ippolito^{132a,132b}, A. Irles Quiles¹⁶⁷, C. Isaksson¹⁶⁶, M. Ishino⁶⁷, M. Ishitsuka¹⁵⁷, R. Ishmukhametov⁴⁰, C. Issever¹¹⁸, S. Istina^{19a}, A.V. Ivashin¹²⁸, W. Iwanski³⁹, H. Iwasaki⁶⁵, J.M. Izen⁴¹, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹, M.R. Jaekel³⁰, V. Jain⁶⁰, K. Jakobs⁴⁸, S. Jakobsen³⁶, T. Jakoubek¹²⁵, J. Jakubek¹²⁷, D.K. Jana¹¹¹, E. Jansen⁷⁷, H. Jansen³⁰, A. Jantsch⁹⁹, M. Janus⁴⁸, G. Jarlskog⁷⁹, L. Jeanty⁵⁷, I. Jen-La Plante³¹, D. Jennens⁸⁶, P. Jenni³⁰, A.E. Loevschall-Jensen³⁶, P. Jež³⁶, S. Jézéquel⁵, M.K. Jha^{20a}, H. Ji¹⁷³, W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁶, D. Joffe⁴⁰, M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴², K.A. Johns⁷, K. Jon-And^{146a,146b}, G. Jones¹⁷⁰, R.W.L. Jones⁷¹, T.J. Jones⁷³, C. Joram³⁰, P.M. Jorge^{124a}, K.D. Joshi⁸², J. Jovicevic¹⁴⁷, T. Jovin^{13b}, X. Ju¹⁷³, C.A. Jung⁴³, R.M. Jungst³⁰, V. Juraneck¹²⁵, P. Jussel⁶¹, A. Juste Rozas¹², S. Kabana¹⁷, M. Kaci¹⁶⁷, A. Kaczmarska³⁹, P. Kadlecik³⁶, M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁵, L.V. Kalinovskaya⁶⁴, S. Kama⁴⁰, N. Kanaya¹⁵⁵, M. Kaneda³⁰, S. Kaneti²⁸, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁵, B. Kaplan¹⁰⁸, A. Kapliy³¹, J. Kaplon³⁰, D. Kar⁵³, M. Karagounis²¹, K. Karakostas¹⁰, M. Karnevskiy⁴², V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif¹⁷³, G. Kasieczka^{58b}, R.D. Kass¹⁰⁹, A. Kastanas¹⁴, M. Kataoka⁵, Y. Kataoka¹⁵⁵, E. Katsoufis¹⁰, J. Katzy⁴², V. Kaushik⁷, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵, S. Kazama¹⁵⁵, V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁹, P.T. Keener¹²⁰, R. Kehoe⁴⁰, M. Keil⁵⁴, G.D. Kekelidze⁶⁴, J.S. Keller¹³⁸, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen³⁰, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁵, K. Kessoku¹⁵⁵, J. Keung¹⁵⁸, F. Khalil-zada¹¹, H. Khandanyan^{146a,146b}, A. Khanov¹¹², D. Kharchenko⁶⁴, A. Khodinov⁹⁶, A. Khomich^{58a}, T.J. Khoo²⁸, G. Khoriali²¹, A. Khoroshilov¹⁷⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁴, J. Khubua^{51b}, H. Kim^{146a,146b}, S.H. Kim¹⁶⁰, N. Kimura¹⁷¹, O. Kind¹⁶, B.T. King⁷³, M. King⁶⁶, R.S.B. King¹¹⁸, J. Kirk¹²⁹, A.E. Kiryunin⁹⁹, T. Kishimoto⁶⁶, D. Kisielewska³⁸, T. Kitamura⁶⁶, T. Kittelmann¹²³, K. Kiuchi¹⁶⁰, E. Kladiva^{144b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷², P. Klimek^{146a,146b}, A. Klimentov²⁵, R. Klingenberg⁴³, J.A. Klinger⁸², E.B. Klinkby³⁶, T. Klioutchnikova³⁰, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, N.S. Knecht¹⁵⁸, E. Kneringer⁶¹, E.B.F.G. Knoops⁸³, A. Knue⁵⁴, B.R. Ko⁴⁵, T. Kobayashi¹⁵⁵, M. Kobel⁴⁴, M. Kocian¹⁴³, P. Kodys¹²⁶, K. Köneke³⁰, A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²¹, T. Koffas²⁹, E. Koffeman¹⁰⁵, L.A. Kogan¹¹⁸, S. Kohlmann¹⁷⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴³, G.M. Kolachev^{107,*}, H. Kolanoski¹⁶, V. Kolesnikov⁶⁴, I. Koletsou^{89a}, J. Koll⁸⁸, A.A. Komar⁹⁴, Y. Komori¹⁵⁵, T. Kondo⁶⁵, T. Kono^{42,s}, A.I. Kononov⁴⁸, R. Konoplich^{108,t}, N. Konstantinidis⁷⁷, S. Koperny³⁸, K. Korycyl³⁹, K. Kordas¹⁵⁴, A. Korn¹¹⁸, A. Korol¹⁰⁷, I. Korolkov¹², E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²¹, S. Kotov⁹⁹, V.M. Kotov⁶⁴, A. Kotwal⁴⁵, C. Kourkoumelis⁹, V. Kouskoura¹⁵⁴, A. Koutsman^{159a}, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁸, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J.K. Kraus²¹, S. Kreiss¹⁰⁸, F. Krejci¹²⁷, J. Kretzschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²¹, J. Krstic^{13a}, U. Kruchonak⁶⁴, H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshcheyn⁶⁴, T. Kubota⁸⁶, S. Kuday^{4a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴², D. Kuhn⁶¹, V. Kukhtin⁶⁴, Y. Kulchitsky⁹⁰, S. Kuleshov^{32b}, C. Kummer⁹⁸, M. Kuna⁷⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁶, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, E.S. Kuwertz¹⁴⁷, M. Kuze¹⁵⁷, J. Kvita¹⁴², R. Kwee¹⁶, A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, L. Labarga⁸⁰, J. Labbe⁵, S. Lablak^{135a}, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, H. Lacker¹⁶, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁴, R. Lafaye⁵, B. Laforge⁷⁸, T. Lagouri¹⁷⁶, S. Lai⁴⁸, E. Laisne⁵⁵, M. Lamanna³⁰, L. Lambourne⁷⁷, C.L. Lampen⁷, W. Lampl⁷, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, J.L. Lane⁸², V.S. Lang^{58a}, C. Lange⁴², A.J. Lankford¹⁶³, F. Lanni²⁵, K. Lantzsche¹⁷⁵, S. Laplace⁷⁸, C. Lapoire²¹, J.F. Laporte¹³⁶, T. Lari^{89a}, A. Lerner¹¹⁸, M. Lassnig³⁰, P. Laurelli⁴⁷, V. Lavorini^{37a,37b}, W. Lavrijsen¹⁵, P. Laycock⁷³, O. Le Dortz⁷⁸, E. Le Guirriec⁸³, E. Le Menedeu¹²,

T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹¹⁶, S.C. Lee¹⁵¹, L. Lee¹⁷⁶, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, F. Legger⁹⁸, C. Leggett¹⁵, M. Lehmacher²¹, G. Lehmann Miotto³⁰, X. Lei⁷, M.A.L. Leite^{24d}, R. Leitner¹²⁶, D. Lellouch¹⁷², B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁰⁵, G. Lenzen¹⁷⁵, B. Lenzi³⁰, K. Leonhardt⁴⁴, S. Leontsinis¹⁰, F. Lepold^{58a}, C. Leroy⁹³, J-R. Lessard¹⁶⁹, C.G. Lester²⁸, C.M. Lester¹²⁰, J. Levêque⁵, D. Levin⁸⁷, L.J. Levinson¹⁷², A. Lewis¹¹⁸, G.H. Lewis¹⁰⁸, A.M. Leyko²¹, M. Leyton¹⁶, B. Li⁸³, H. Li^{173,u}, S. Li^{33b,v}, X. Li⁸⁷, Z. Liang^{118,w}, H. Liao³⁴, B. Liberti^{133a}, P. Lichard³⁰, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹⁴, C. Limbach²¹, A. Limosani⁸⁶, M. Limper⁶², S.C. Lin^{151,x}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, A. Lipniacka¹⁴, T.M. Liss¹⁶⁵, D. Lissauer²⁵, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁹, D. Liu¹⁵¹, H. Liu⁸⁷, J.B. Liu⁸⁷, L. Liu⁸⁷, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁷, T. Loddenkoetter²¹, F.K. Loebinger⁸², A. Loginov¹⁷⁶, C.W. Loh¹⁶⁸, T. Lohse¹⁶, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, V.P. Lombardo⁵, R.E. Long⁷¹, L. Lopes^{124a}, D. Lopez Mateos⁵⁷, J. Lorenz⁹⁸, N. Lorenzo Martinez¹¹⁵, M. Losada¹⁶², P. Loscutoff¹⁵, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a,*}, X. Lou⁴¹, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love⁶, P.A. Love⁷¹, A.J. Lowe^{143,e}, F. Lu^{33a}, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴⁴, D. Ludwig⁴², I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰, G. Luijckx¹⁰⁵, W. Lukas⁶¹, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, O. Lundberg^{146a,146b}, J. Lundquist³⁶, M. Lungwitz⁸¹, D. Lynn²⁵, E. Lytken⁷⁹, H. Ma²⁵, L.L. Ma¹⁷³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a}, R. Mackeprang³⁶, R.J. Madaras¹⁵, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, R. Maenner^{58c}, T. Maeno²⁵, P. Mättig¹⁷⁵, S. Mättig⁸¹, L. Magnoni¹⁶³, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁵, S. Mahmoud⁷³, G. Mahout¹⁸, C. Maiani¹³⁶, C. Maidantchik^{24a}, A. Maio^{124a,b}, S. Majewski²⁵, Y. Makida⁶⁵, N. Makovec¹¹⁵, P. Mal¹³⁶, B. Malaescu³⁰, Pa. Malecki³⁹, P. Malecki³⁹, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶, C. Malone¹⁴³, S. Maltezos¹⁰, V. Malyshev¹⁰⁷, S. Malyukov³⁰, R. Mameghani⁹⁸, J. Mamuzic^{13b}, A. Manabe⁶⁵, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁶, J. Maneira^{124a}, A. Manfredini⁹⁹, P.S. Mangeard⁸⁸, L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos¹³⁶, A. Mann⁵⁴, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁶, A. Mapelli³⁰, L. Mapelli³⁰, L. March⁸⁰, J.F. Marchand²⁹, F. Marchese^{133a,133b}, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, C.P. Marino¹⁶⁹, F. Marroquim^{24a}, Z. Marshall³⁰, F.K. Martens¹⁵⁸, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁷, B. Martin³⁰, B. Martin⁸⁸, J.P. Martin⁹³, T.A. Martin¹⁸, V.J. Martin⁴⁶, B. Martin dit Latour⁴⁹, S. Martin-Haugh¹⁴⁹, M. Martinez¹², V. Martinez Outschoorn⁵⁷, A.C. Martyniuk¹⁶⁹, M. Marx⁸², F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, I. Massa^{20a,20b}, G. Massaro¹⁰⁵, N. Massol⁵, P. Mastrandrea¹⁴⁸, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁵, P. Matricon¹¹⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁶, C. Mattravers^{118,c}, J. Maurer⁸³, S.J. Maxfield⁷³, A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²¹, L. Mazzaferro^{133a,133b}, M. Mazzanti^{89a}, J. Mc Donald⁸⁵, S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁹, N.A. McCubbin¹²⁹, K.W. McFarlane^{56,*}, J.A. Mcfayden¹³⁹, G. Mchedlidze^{51b}, T. McLaughlan¹⁸, S.J. McMahon¹²⁹, R.A. McPherson^{169,k}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁵, M. Medinnis⁴², R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶, R. Mehdiyev⁹³, S. Mehlhase³⁶, A. Mehta⁷³, K. Meier^{58a}, B. Meirose⁷⁹, C. Melachrinou³¹, B.R. Mellado Garcia¹⁷³, F. Meloni^{89a,89b}, L. Mendoza Navas¹⁶², Z. Meng^{151,u}, A. Mengarelli^{20a,20b}, S. Menke⁹⁹, E. Meoni¹⁶¹, K.M. Mercurio⁵⁷, P. Mermod⁴⁹, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³¹, H. Merritt¹⁰⁹, A. Messina^{30,y}, J. Metcalfe²⁵, A.S. Mete¹⁶³, C. Meyer⁸¹, C. Meyer³¹, J-P. Meyer¹³⁶, J. Meyer¹⁷⁴, J. Meyer⁵⁴, T.C. Meyer³⁰, J. Miao^{33d}, S. Michal³⁰, L. Micu^{26a}, R.P. Middleton¹²⁹, S. Migas⁷³, L. Mijović¹³⁶, G. Mikenberg¹⁷², M. Mikestikova¹²⁵, M. Mikuž⁷⁴, D.W. Miller³¹, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷², D.A. Milstead^{146a,146b}, D. Milstein¹⁷², A.A. Minaenko¹²⁸, M. Miñano Moya¹⁶⁷, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁸, B. Mindur³⁸, M. Mineev⁶⁴, Y. Ming¹⁷³, L.M. Mir¹², G. Mirabelli^{132a}, J. Mitrevski¹³⁷, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁵, P.S. Miyagawa¹³⁹, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, V. Moeller²⁸, K. Mönig⁴², N. Möser²¹, S. Mohapatra¹⁴⁸, W. Mohr⁴⁸, R. Moles-Valls¹⁶⁷, A. Molfetas³⁰, J. Monk⁷⁷, E. Monnier⁸³, J. Montejo Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{20a,20b}, R.W. Moore³, G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{37a,37b}, D. Moreno⁸¹, M. Moreno Llacer¹⁶⁷, P. Morettini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁷, A.K. Morley³⁰, G. Mornacchi³⁰, J.D. Morris⁷⁵, L. Morvaj¹⁰¹, H.G. Moser⁹⁹, M. Mosidze^{51b}, J. Moss¹⁰⁹, R. Mount¹⁴³, E. Mountricha^{10,z}, S.V. Mouraviev^{94,*}, E.J.W. Moyses⁸⁴, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²¹, T.A. Müller⁹⁸, T. Mueller⁸¹, D. Muenstermann³⁰, Y. Munwes¹⁵³, W.J. Murray¹²⁹, I. Mussche¹⁰⁵, E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹², K. Nagai¹⁶⁰, R. Nagai¹⁵⁷, K. Nagano⁶⁵, A. Nagarkar¹⁰⁹, Y. Nagasaka⁵⁹, M. Nagel⁹⁹, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura¹⁵⁵, T. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²¹, A. Napier¹⁶¹, R. Narayan^{58b}, M. Nash^{77,c}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶², H.A. Neal⁸⁷, P.Yu. Nechaeva⁹⁴, T.J. Neep⁸², A. Negri^{119a,119b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, A. Nelson¹⁶³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{24a}, M. Nessi^{30,aa}, M.S. Neubauer¹⁶⁵, M. Neumann¹⁷⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁵, F.M. Newcomer¹²⁰, P.R. Newman¹⁸, V. Nguyen Thi Hong¹³⁶, R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, B. Nicquevert³⁰, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, N. Niki-forou³⁵, A. Nikiforov¹⁶, V. Nikolaenko¹²⁸, I. Nikolic-Audit⁷⁸, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, H. Nilsen⁴⁸, P. Nils-son⁸, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, R. Nisius⁹⁹, T. Nobe¹⁵⁷, L. Nodulman⁶, M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, S. Nor-

berg¹¹¹, M. Nordberg³⁰, P.R. Norton¹²⁹, J. Novakova¹²⁶, M. Nozaki⁶⁵, L. Nozka¹¹³, I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²¹, G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷, B.J. O'Brien⁴⁶, D.C. O'Neil¹⁴², V. O'Shea⁵³, L.B. Oakes⁹⁸, F.G. Oakham^{29,d}, H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁶, S. Oda⁶⁹, S. Odaka⁶⁵, J. Odier⁸³, H. Ogren⁶⁰, A. Oh⁸², S.H. Oh⁴⁵, C.C. Ohm³⁰, T. Ohshima¹⁰¹, H. Okawa²⁵, Y. Okumura³¹, T. Okuyama¹⁵⁵, A. Olariu^{26a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino^{32a}, M. Oliveira^{124a,h}, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{124a,ab}, P.U.E. Onyisi³¹, C.J. Oram^{159a}, M.J. Oreglia³¹, Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{72a,72b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹², G. Otero y Garzon²⁷, J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135d}, E.A. Ouellette¹⁶⁹, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸², S. Owen¹³⁹, V.E. Ozcan^{19a}, N. Ozturk⁸, A. Pacheco Pages¹², C. Padilla Aranda¹², S. Pagan Griso¹⁵, E. Paganis¹³⁹, C. Pahl⁹⁹, F. Paige²⁵, P. Pais⁸⁴, K. Pajchel¹¹⁷, G. Palacino^{159b}, C.P. Paleari⁷, S. Palestini³⁰, D. Pallin³⁴, A. Palma^{124a}, J.D. Palmer¹⁸, Y.B. Pan¹⁷³, E. Panagiotopoulou¹⁰, P. Pani¹⁰⁵, N. Panikashvili⁸⁷, S. Panitkin²⁵, D. Pantea^{26a}, A. Papadellis^{146a}, Th.D. Papadopoulos¹⁰, A. Paramonov⁶, D. Paredes Hernandez³⁴, W. Park^{25,ac}, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, S. Pashapour⁵⁴, E. Pasqualucci^{132a}, S. Passaggio^{50a}, A. Passeri^{134a}, F. Pastore^{134a,134b,*}, Fr. Pastore⁷⁶, G. Pásztor^{49,ad}, S. Pataria¹⁷⁵, N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly³⁰, M. Pecsly^{144a}, S. Pedraza Lopez¹⁶⁷, M.I. Pedraza Morales¹⁷³, S.V. Peleganchuk¹⁰⁷, D. Pelikan¹⁶⁶, H. Peng^{33b}, B. Penning³¹, A. Penson³⁵, J. Penwell⁶⁰, M. Perantoni^{24a}, K. Perez^{35,ae}, T. Perez Cavalcanti⁴², E. Perez Codina^{159a}, M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁵, L. Perini^{89a,89b}, H. Pernegger³⁰, R. Perrino^{72a}, P. Perrodo⁵, V.D. Peshekhonov⁶⁴, K. Peters³⁰, B.A. Petersen³⁰, J. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁵, A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolo^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴², M. Petteni¹⁴², R. Pezoa^{32b}, A. Phan⁸⁶, P.W. Phillips¹²⁹, G. Piacquadio³⁰, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, S.M. Piec⁴², R. Piegai²⁷, D.T. Pignotti¹⁰⁹, J.E. Pilcher³¹, A.D. Pilkington⁸², J. Pina^{124a,b}, M. Pina-monti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold³, B. Pinto^{124a}, C. Pizio^{89a,89b}, M. Plamondon¹⁶⁹, M.-A. Pleier²⁵, E. Plotnikova⁶⁴, A. Poblaguev²⁵, S. Poddar^{58a}, F. Podlyski³⁴, L. Poggioni¹¹⁵, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{119a}, A. Policicchio^{37a,37b}, A. Polini^{20a}, J. Poll⁷⁵, V. Polychronakos²⁵, D. Pomeroy²³, K. Pommès³⁰, L. Pontecorvo^{132a}, B.G. Pope⁸⁸, G.A. Popeneciu^{26a}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso³⁰, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴, G. Poulard³⁰, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, R. Prabhu⁷⁷, P. Pralavorio⁸³, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan²⁵, S. Prell⁶³, K. Pretzl¹⁷, D. Price⁶⁰, J. Price⁷³, L.E. Price⁶, D. Prieur¹²³, M. Primavera⁷⁵, K. Prokofiev¹⁰⁸, F. Prokoshin^{32b}, S. Protopopescu²⁵, J. Proudfoot⁶, X. Prudent⁴⁴, M. Przybycien³⁸, H. Przysiezniak⁵, S. Psoroulas²¹, E. Ptacek¹¹⁴, E. Pueschel⁸⁴, J. Purdham⁸⁷, M. Purohit^{25,ac}, P. Puzo¹¹⁵, Y. Pylypchenko⁶², J. Qian⁸⁷, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle¹⁷³, F. Quinonez^{32a}, M. Raas¹⁰⁴, V. Radeka²⁵, V. Radescu⁴², P. Radloff¹¹⁴, T. Rador^{19a}, F. Ragusa^{89a,89b}, G. Rahal¹⁷⁸, A.M. Rahimi¹⁰⁹, D. Rahm²⁵, S. Rajagopalan²⁵, M. Rammensee⁴⁸, M. Rammes¹⁴¹, A.S. Randle-Conde⁴⁰, K. Randrianarivony²⁹, F. Rauscher⁹⁸, T.C. Rave⁴⁸, M. Raymond³⁰, A.L. Read¹¹⁷, D.M. Rebuzzi^{119a,119b}, A. Redelbach¹⁷⁴, G. Redlinger²⁵, R. Reece¹²⁰, K. Reeves⁴¹, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴³, C. Rembser³⁰, Z.L. Ren¹⁵¹, A. Renaud¹¹⁵, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, R. Richter⁹⁹, E. Richter-Was^{5,af}, M. Ridel⁷⁸, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{20a}, R.R. Rios⁴⁰, I. Riu¹², G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,k}, A. Robichaud-Veronneau¹¹⁸, D. Robinson²⁸, J.E.M. Robinson⁸², A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b}, D. Roda Dos Santos³⁰, A. Roe⁵⁴, S. Roe³⁰, O. Röhne¹¹⁷, S. Rolli¹⁶¹, A. Romaniouk⁹⁶, M. Romano^{20a,20b}, G. Romeo²⁷, E. Romero Adam¹⁶⁷, N. Rompotis¹³⁸, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati^{132a}, K. Rosbach⁴⁹, A. Rose¹⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶³, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴¹, L. Rossetlet⁴⁹, V. Rossetti¹², E. Rossi^{132a,132b}, L.P. Rossi^{50a}, M. Rotaru^{26a}, I. Roth¹⁷², J. Rothberg¹³⁸, D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan^{33a,ag}, F. Rubbo¹², I. Rubinskiy⁴², N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴⁴, G. Rudolph⁶¹, F. Rühr⁷, A. Ruiz-Martinez⁶³, L. Rummyantsev⁶⁴, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, J.P. Rutherford⁷, C. Ruwiedel^{15,*}, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, M. Rybar¹²⁶, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁴, F. Safai Tehrani^{132a}, H. Sakamoto¹⁵⁵, G. Salamanna⁷⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salek³⁰, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁶, D. Salvatore^{37a,37b}, F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴, A. Salzburger³⁰, D. Sampsonidis¹⁵⁴, B.H. Samsel¹¹⁷, A. Sanchez^{102a,102b}, V. Sanchez Martinez¹⁶⁷, H. Sandaker¹⁴, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁵, T. Sandoval²⁸, C. Sandoval¹⁶², R. Sandstroem⁹⁹, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³⁴, R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a}, T. Sarangi¹⁷³, E. Sarkisyan-Grinbaum⁸, F. Sarri^{122a,122b}, G. Sartiso¹⁷⁵, O. Sasaki⁶⁵, Y. Sasaki¹⁵⁵, N. Sasao⁶⁷, I. Satsounkevitch⁹⁰, G. Sauvage^{5,*}, E. Sauvan⁵, J.B. Sauvan¹¹⁵, P. Savard^{158,d}, V. Savinov¹²³, D.O. Savu³⁰, L. Sawyer^{25,m}, D.H. Saxon⁵³, J. Saxon¹²⁰, C. Sbarra^{20a}, A. Sbrizzi^{20a,20b}, D.A. Scannicchio¹⁶³, M. Scarcella¹⁵⁰, J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹, D. Schaefer¹²⁰, U. Schäfer⁸¹, S. Schaepe²¹, S. Schaezel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³, M.I. Scherzer³⁵, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden²¹, C. Schmitt⁸¹, S. Schmitt^{58b},

M. Schmitz²¹, B. Schneider¹⁷, U. Schnoor⁴⁴, A. Schoening^{58b}, A.L.S. Schorlemmer⁵⁴, M. Schott³⁰, D. Schouten^{159a}, J. Schovancova¹²⁵, M. Schram⁸⁵, C. Schroeder⁸¹, N. Schroer^{58c}, M.J. Schultens²¹, J. Schultes¹⁷⁵, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸², A. Schwartzman¹⁴³, Ph. Schwemmer⁹⁹, Ph. Schwemling⁷⁸, R. Schwiehorst⁸⁸, R. Schwier⁴⁴, J. Schwindling¹³⁶, T. Schwindt²¹, M. Schwoerer⁵, G. Sciolla²³, W.G. Scott¹²⁹, J. Searcy¹¹⁴, G. Sedov⁴², E. Sedykh¹²¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴⁴, J.M. Seixas^{24a}, G. Sekhniaidze^{102a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{20a,20b}, C. Serfon⁹⁸, L. Serin¹¹⁵, L. Serkin⁵⁴, R. Seuster⁹⁹, H. Severini¹¹¹, A. Sfyrila³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{33a}, J.T. Shank²², Q.T. Shao⁸⁶, M. Shapiro¹⁵, P.B. Shatalov⁹⁵, K. Shaw^{164a,164c}, D. Sherman¹⁷⁶, P. Sherwood⁷⁷, S. Shimizu¹⁰¹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁴, M.J. Shochet³¹, D. Short¹¹⁸, S. Shrestha⁶³, E. Shulga⁹⁶, M.A. Shupe⁷, P. Sicho¹²⁵, A. Sidoti^{132a}, F. Siegert⁴⁸, Dj. Sijacki^{13a}, O. Silbert¹⁷², J. Silva^{124a}, Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷, O. Simard¹³⁶, Lj. Simic^{13a}, S. Simion¹¹⁵, E. Simioni⁸¹, B. Simmons⁷⁷, R. Simoniello^{89a,89b}, M. Simonyan³⁶, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa¹⁷⁴, A. Sircar²⁵, A.N. Sisakyan^{64,*}, S.Yu. Sivoklov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjursen¹⁴, L.A. Skinnari¹⁵, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, M. Slater¹⁸, T. Slavicek¹²⁷, K. Sliwa¹⁶¹, V. Smakhtin¹⁷², B.H. Smart⁴⁶, L. Smestad¹¹⁷, S.Yu. Smirnov⁹⁶, Y. Smirnov⁹⁶, L.N. Smirnova⁹⁷, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹, S. Snyder²⁵, R. Sobie^{169,k}, J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁶, U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸, V. Solovyev¹²¹, N. Soni¹, V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sosebee⁸, R. Soualah^{164a,164c}, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, R. Spighi^{20a}, G. Spigo³⁰, R. Spiwoks³⁰, M. Spousta^{126,ah}, T. Spreitzer¹⁵⁸, B. Spurlock⁸, R.D. St. Denis⁵³, J. Stahlman¹²⁰, R. Stamen^{58a}, E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{134a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁴², R. Staszewski³⁹, A. Staude⁹⁸, P. Stavina^{144a,*}, G. Steele⁵³, P. Steinbach⁴⁴, P. Steinberg²⁵, I. Stekl¹²⁷, B. Stelzer¹⁴², H.J. Stelzer⁸⁸, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², S. Stern⁹⁹, G.A. Stewart³⁰, J.A. Stillings²¹, M.C. Stockton⁸⁵, K. Stoerig⁴⁸, G. Stoicea^{26a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁸, A. Straessner⁴⁴, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷⁴, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski⁴⁰, J. Strube¹²⁹, B. Stugu¹⁴, I. Stumer^{25,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁵, N.A. Styles⁴², D.A. Soh^{151,w}, D. Su¹⁴³, H.S. Subramania³, A. Succurro¹², Y. Sugaya¹¹⁶, C. Suhr¹⁰⁶, M. Suk¹²⁶, V.V. Sulin⁹⁴, S. Sultansoy^{4d}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹³⁹, G. Susinno^{37a,37b}, M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶, M. Svatos¹²⁵, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁶, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴², A. Taffard¹⁶³, R. Tafirout^{159a}, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹, H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴⁰, Y. Takubo⁶⁵, M. Talby⁸³, A. Talyshev^{107,f}, M.C. Tamssett²⁵, K.G. Tan⁸⁶, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴², K. Tani⁶⁶, N. Tannoury⁸³, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁹, G.F. Tartarelli^{89a}, P. Tas¹²⁶, M. Tasevsky¹²⁵, E. Tassi^{37a,37b}, M. Tatarkhanov¹⁵, Y. Tayalati^{135d}, C. Taylor⁷⁷, F.E. Taylor⁹², G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teinturier¹¹⁵, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵¹, S. Terada⁶⁵, K. Terashi¹⁵⁵, J. Teron⁸⁰, M. Testa⁴⁷, R.J. Teuscher^{158,k}, J. Therhaag²¹, T. Thevenaux-Pelzer⁷⁸, S. Thoma⁴⁸, J.P. Thomas¹⁸, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²⁰, M. Thomson²⁸, W.M. Thong⁸⁶, R.P. Thun⁸⁷, F. Tian³⁵, M.J. Tibbetts¹⁵, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴, Y.A. Tikhonov^{107,f}, S. Timoshenko⁹⁶, P. Tipton¹⁷⁶, S. Tisserant⁸³, T. Todorov⁵, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁹, S. Tokár^{144a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins³¹, K. Toms¹⁰³, A. Tonoyan¹⁴, C. Topfel¹⁷, N.D. Topilin⁶⁴, I. Torchiani³⁰, E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torró Pastor¹⁶⁷, J. Toth^{83,ad}, F. Touchard⁸³, D.R. Tovey¹³⁹, T. Trefzger¹⁷⁴, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{159a}, S. Trincas-Duvold⁷⁸, M.F. Tripijana⁷⁰, N. Triplett²⁵, W. Trischuk¹⁵⁸, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trotter-McDonald¹⁴², M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C.-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiarehska⁹⁰, D. Tsionou^{5,ai}, G. Tsipolitis¹⁰, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁵, J.-W. Tsung²¹, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, A. Tudorache^{26a}, V. Tudorache^{26a}, J.M. Tuggle³¹, M. Turala³⁹, D. Turecek¹²⁷, I. Turk Cakir^{4e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b}, P.M. Tuts³⁵, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b}, M. Tyn del¹²⁹, G. Tzanakos⁹, K. Uchida²¹, I. Ueda¹⁵⁵, R. Ueno²⁹, M. Ugland¹⁴, M. Uhlenbrock²¹, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶³, Y. Unno⁶⁵, D. Urbaniec³⁵, P. Urquijo²¹, G. Usai⁸, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁵, J. Valenta¹²⁵, S. Valentinetti^{20a,20b}, A. Valero¹⁶⁷, S. Valkar¹²⁶, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, R. Van Berg¹²⁰, P.C. Van Der Deijl¹⁰⁵, R. van der Geer¹⁰⁵, H. van der Graaf¹⁰⁵, R. Van Der Leeuw¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, I. van Vulpen¹⁰⁵, M. Vanadia⁹⁹, W. Vandelli³⁰, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁸, R. Vari^{132a}, T. Varol⁸⁴, D. Varouchas¹⁵, A. Vartapetian⁸, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, F. Veloso^{124a}, R. Veness³⁰, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura⁸⁴, M. Venturi⁴⁸, N. Venturi¹⁵⁸, V. Vercesi^{119a},

M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, A. Vest⁴⁴, M.C. Vetterli^{142,d}, I. Vichou¹⁶⁵, T. Vickey^{145b,aj}, O.E. Vickey Boeriu^{145b}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{20a,20b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vinciter²⁹, E. Vinek³⁰, V.B. Vinogradov⁶⁴, M. Virchaux^{136,*}, J. Virzi¹⁵, O. Vitells¹⁷², M. Viti⁴², I. Vivarelli⁴⁸, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁸, M. Vlasak¹²⁷, A. Vogel²¹, P. Vokac¹²⁷, G. Volpi⁴⁷, M. Volpi⁸⁶, G. Volpini^{89a}, H. von der Schmitt⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁶, V. Vorwerk¹², M. Vos¹⁶⁷, R. Voss³⁰, T.T. Voss¹⁷⁵, J.H. Vossebeld⁷³, N. Vranjes¹³⁶, M. Vranjes Milosavljevic¹⁰⁵, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, W. Wagner¹⁷⁵, P. Wagner¹²⁰, H. Wahlen¹⁷⁵, S. Wahrmund⁴⁴, J. Wakabayashi¹⁰¹, S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁶, P. Waller⁷³, B. Walsh¹⁷⁶, C. Wang⁴⁵, H. Wang¹⁷³, H. Wang^{33b,ak}, J. Wang¹⁵¹, J. Wang⁵⁵, R. Wang¹⁰³, S.M. Wang¹⁵¹, T. Wang²¹, A. Warburton⁸⁵, C.P. Ward²⁸, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², I. Watanabe⁶⁶, P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵⁰, M.F. Watson¹⁸, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, M.S. Weber¹⁷, P. Weber⁵⁴, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹, J. Weingarten⁵⁴, C. Weiser⁴⁸, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{151,w}, T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Werth¹⁶³, M. Wessels^{58a}, J. Wetter¹⁶¹, C. Weydert⁵⁵, K. Whalen²⁹, S.J. Wheeler-Ellis¹⁶³, A. White⁸, M.J. White⁸⁶, S. White^{122a,122b}, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶⁰, F. Wicke¹¹⁵, D. Wicke¹⁷⁵, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷³, M. Wielers¹²⁹, P. Wienemann²¹, C. Wiglesworth⁷⁵, L.A.M. Wiik-Fuchs⁴⁸, P.A. Wijeratne⁷⁷, A. Wildauer⁹⁹, M.A. Wildt^{42,s}, I. Wilhelm¹²⁶, H.G. Wilkens³⁰, J.Z. Will⁹⁸, E. Williams³⁵, H.H. Williams¹²⁰, W. Willis³⁵, S. Willocq⁸⁴, J.A. Wilson¹⁸, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁵, S. Winkelmann⁴⁸, F. Winklmeier³⁰, M. Wittgen¹⁴³, S.J. Wollstadt⁸¹, M.W. Wolter³⁹, H. Wolters^{124a,h}, W.C. Wong⁴¹, G. Wooden⁸⁷, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸², K.W. Wozniak³⁹, K. Wraight⁵³, M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷³, X. Wu⁴⁹, Y. Wu^{33b,al}, E. Wulf³⁵, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁶, S. Xie⁴⁸, C. Xu^{33b,z}, D. Xu¹³⁹, B. Yabsley¹⁵⁰, S. Yacoub^{145a,am}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁵, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, T. Yamanaka¹⁵⁵, J. Yamaoka⁴⁵, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁶, Z. Yan²², H. Yang⁸⁷, U.K. Yang⁸², Y. Yang¹⁰⁹, Z. Yang^{146a,146b}, S. Yanush⁹¹, L. Yao^{33a}, Y. Yao¹⁵, Y. Yasu⁶⁵, G.V. Ybeles Smit¹³⁰, J. Ye⁴⁰, S. Ye²⁵, M. Yilmaz^{4c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷¹, R. Yoshida⁶, C. Young¹⁴³, C.J. Young¹¹⁸, S. Youssef²², D. Yu²⁵, J. Yu⁸, J. Yu¹¹², L. Yuan⁶⁶, A. Yurkewicz¹⁰⁶, M. Byszewski³⁰, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev¹²⁸, Z. Zajacova³⁰, L. Zanello^{132a,132b}, D. Zanzi⁹⁹, A. Zaytsev²⁵, C. Zeitnitz¹⁷⁵, M. Zeman¹²⁵, A. Zemla³⁹, C. Zendler²¹, O. Zenin¹²⁸, T. Ženiš^{144a}, Z. Zinonos^{122a,122b}, S. Zenz¹⁵, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, Z. Zhan^{33d}, D. Zhang^{33b,ak}, H. Zhang⁸⁸, J. Zhang⁶, X. Zhang^{33d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁸, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{33d}, H. Zhu⁴², J. Zhu⁸⁷, Y. Zhu^{33b}, X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶⁰, N.I. Zimin⁶⁴, R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁵, L. Živković³⁵, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷³, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, V. Zutshi¹⁰⁶, L. Zwalinski³⁰

¹School of Chemistry and Physics, University of Adelaide, Adelaide, Australia

²Physics Department, SUNY Albany, Albany NY, United States of America

³Department of Physics, University of Alberta, Edmonton AB, Canada

^{4(a)}Department of Physics, Ankara University, Ankara; ^(b)Department of Physics, Dumlupinar University, Kutahya;

^(c)Department of Physics, Gazi University, Ankara; ^(d)Division of Physics, TOBB University of Economics and Technology, Ankara; ^(e)Turkish Atomic Energy Authority, Ankara, Turkey

⁵LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

⁷Department of Physics, University of Arizona, Tucson AZ, United States of America

⁸Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

⁹Physics Department, University of Athens, Athens, Greece

¹⁰Physics Department, National Technical University of Athens, Zografou, Greece

¹¹Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹²Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

^{13(a)}Institute of Physics, University of Belgrade, Belgrade; ^(b)Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹⁴Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

¹⁶Department of Physics, Humboldt University, Berlin, Germany

- ¹⁷Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁸School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ¹⁹(a)Department of Physics, Bogazici University, Istanbul; (b)Division of Physics, Dogus University, Istanbul; (c)Department of Physics Engineering, Gaziantep University, Gaziantep; (d)Department of Physics, Istanbul Technical University, Istanbul, Turkey
- ²⁰(a)INFN Sezione di Bologna; (b)Dipartimento di Fisica, Università di Bologna, Bologna, Italy
- ²¹Physikalisches Institut, University of Bonn, Bonn, Germany
- ²²Department of Physics, Boston University, Boston MA, United States of America
- ²³Department of Physics, Brandeis University, Waltham MA, United States of America
- ²⁴(a)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b)Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c)Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d)Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁵Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- ²⁶(a)National Institute of Physics and Nuclear Engineering, Bucharest; (b)University Politehnica Bucharest, Bucharest; (c)West University in Timisoara, Timisoara, Romania
- ²⁷Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁸Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ²⁹Department of Physics, Carleton University, Ottawa ON, Canada
- ³⁰CERN, Geneva, Switzerland
- ³¹Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- ³²(a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³³(a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b)Department of Modern Physics, University of Science and Technology of China, Anhui; (c)Department of Physics, Nanjing University, Jiangsu; (d)School of Physics, Shandong University, Shandong, China
- ³⁴Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ³⁶Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁷(a)INFN Gruppo Collegato di Cosenza; (b)Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
- ³⁸AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ³⁹The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰Physics Department, Southern Methodist University, Dallas TX, United States of America
- ⁴¹Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴²DESY, Hamburg and Zeuthen, Germany
- ⁴³Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁵Department of Physics, Duke University, Durham NC, United States of America
- ⁴⁶SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁴⁹Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰(a)INFN Sezione di Genova; (b)Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹(a)E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; (b)High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵²II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶Department of Physics, Hampton University, Hampton VA, United States of America
- ⁵⁷Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

- ^{58(a)}Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c)ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰Department of Physics, Indiana University, Bloomington IN, United States of America
- ⁶¹Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶²University of Iowa, Iowa City IA, United States of America
- ⁶³Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- ⁶⁴Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸Kyoto University of Education, Kyoto, Japan
- ⁶⁹Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹Physics Department, Lancaster University, Lancaster, United Kingdom
- ^{72(a)}INFN Sezione di Lecce; ^(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁶Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁹Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁰Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸¹Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸²School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸³CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁴Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁸⁵Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁶School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁷Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ⁸⁸Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ^{89(a)}INFN Sezione di Milano; ^(b)Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁰B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹¹National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹²Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- ⁹³Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁴P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁵Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁶Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁷Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁸Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁹Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁰Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰¹Graduate School of Science and Kobayashi–Maskawa Institute, Nagoya University, Nagoya, Japan
- ^{102(a)}INFN Sezione di Napoli; ^(b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰³Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁴Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁵Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁶Department of Physics, Northern Illinois University, DeKalb IL, United States of America

- ¹⁰⁷Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁸Department of Physics, New York University, New York NY, United States of America
- ¹⁰⁹Ohio State University, Columbus OH, United States of America
- ¹¹⁰Faculty of Science, Okayama University, Okayama, Japan
- ¹¹¹Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹²Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹³Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁴Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁵LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁶Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁷Department of Physics, University of Oslo, Oslo, Norway
- ¹¹⁸Department of Physics, Oxford University, Oxford, United Kingdom
- ^{119(a)}INFN Sezione di Pavia; ^(b)Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²⁰Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- ¹²¹Petersburg Nuclear Physics Institute, Gatchina, Russia
- ^{122(a)}INFN Sezione di Pisa; ^(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²³Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- ^{124(a)}Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; ^(b)Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- ¹²⁵Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁶Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹²⁷Czech Technical University in Prague, Praha, Czech Republic
- ¹²⁸State Research Center Institute for High Energy Physics, Protvino, Russia
- ¹²⁹Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³⁰Physics Department, University of Regina, Regina SK, Canada
- ¹³¹Ritsumeikan University, Kusatsu, Shiga, Japan
- ^{132(a)}INFN Sezione di Roma I; ^(b)Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- ^{133(a)}INFN Sezione di Roma Tor Vergata; ^(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ^{134(a)}INFN Sezione di Roma Tre; ^(b)Dipartimento di Fisica, Università Roma Tre, Roma, Italy
- ^{135(a)}Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b)Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; ^(d)Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda; ^(e)Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- ¹³⁶DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France
- ¹³⁷Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- ¹³⁸Department of Physics, University of Washington, Seattle WA, United States of America
- ¹³⁹Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴⁰Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴¹Fachbereich Physik, Universität Siegen, Siegen, Germany
- ¹⁴²Department of Physics, Simon Fraser University, Burnaby BC, Canada
- ¹⁴³SLAC National Accelerator Laboratory, Stanford CA, United States of America
- ^{144(a)}Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ^{145(a)}Department of Physics, University of Johannesburg, Johannesburg; ^(b)School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ^{146(a)}Department of Physics, Stockholm University; ^(b)The Oskar Klein Centre, Stockholm, Sweden
- ¹⁴⁷Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁴⁸Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- ¹⁴⁹Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵⁰School of Physics, University of Sydney, Sydney, Australia

- ¹⁵¹Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵²Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- ¹⁵³Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵⁴Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁵International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁶Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁷Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁸Department of Physics, University of Toronto, Toronto ON, Canada
- ^{159(a)}TRIUMF, Vancouver BC; ^(b)Department of Physics and Astronomy, York University, Toronto ON, Canada
- ¹⁶⁰Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- ¹⁶¹Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- ¹⁶²Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ¹⁶³Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- ^{164(a)}INFN Gruppo Collegato di Udine, Udine; ^(b)ICTP, Trieste; ^(c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁵Department of Physics, University of Illinois, Urbana IL, United States of America
- ¹⁶⁶Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁷Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁶⁸Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁶⁹Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁷⁰Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷¹Waseda University, Tokyo, Japan
- ¹⁷²Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷³Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁴Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁵Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁶Department of Physics, Yale University, New Haven CT, United States of America
- ¹⁷⁷Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁸Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ^aAlso at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- ^bAlso at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- ^cAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ^dAlso at TRIUMF, Vancouver BC, Canada
- ^eAlso at Department of Physics, California State University, Fresno CA, United States of America
- ^fAlso at Novosibirsk State University, Novosibirsk, Russia
- ^gAlso at Fermilab, Batavia IL, United States of America
- ^hAlso at Department of Physics, University of Coimbra, Coimbra, Portugal
- ⁱAlso at Department of Physics, UASLP, San Luis Potosi, Mexico
- ^jAlso at Università di Napoli Parthenope, Napoli, Italy
- ^kAlso at Institute of Particle Physics (IPP), Canada
- ^lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey
- ^mAlso at Louisiana Tech University, Ruston LA, United States of America
- ⁿAlso at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ^oAlso at Department of Physics and Astronomy, University College London, London, United Kingdom
- ^pAlso at Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ^qAlso at Department of Physics, University of Cape Town, Cape Town, South Africa
- ^rAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^sAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^tAlso at Manhattan College, New York NY, United States of America

^uAlso at School of Physics, Shandong University, Shandong, China

^vAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

^wAlso at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

^xAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

^yAlso at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

^zAlso at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France

^{aa}Also at Section de Physique, Université de Genève, Geneva, Switzerland

^{ab}Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal

^{ac}Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

^{ad}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

^{ae}Also at California Institute of Technology, Pasadena CA, United States of America

^{af}Also at Institute of Physics, Jagiellonian University, Krakow, Poland

^{ag}Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

^{ah}Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America

^{ai}Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

^{aj}Also at Department of Physics, Oxford University, Oxford, United Kingdom

^{ak}Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

^{al}Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

^{am}Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

*Deceased